Tracking environmental pressures from recreational boating

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Abstract of the master's thesis

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Abstract

Compared to land-based activities, environmental legislation considering marine transport sector has developed slowly. During last decades, concern about sustainability of the marine sector has increased, but emission inventories and regulations have mainly focused on commercial vessels. Main reason for this is presumably a lack of data about recreational watercraft. This thesis aimed at recognising sources of emission from the operation of recreational watercraft and discussing different methods for tracking the recreational watercraft activity. A global Automatic Identification System (AIS) dataset was used to generate the geographical and temporal distributions of the activity of recreational watercraft. Previous studies show that volatile hydrocarbons, carbon monoxide, oxides of nitrogen, particulate matter and carbon dioxide are the major airborne emissions from recreational watercraft. As the contribution of recreational watercraft to the climate change is small, emissions affecting the ambient air quality can be considered to be more significant than the greenhouse gas emissions. The most significant emissions to water include hydrocarbons, biocides of antifouling paints and wastewater. Variation in the emission rates is large as the rate depends on the boat and the engine technology, but also on the behaviour of the boater. An algorithm was built for the identification of recreational watercraft from AIS dataset. Identification was based on the existing knowledge about boat usage. Identified watercraft were studied to obtain spatial and temporal activity profiles. According to the results, AIS can be used for tracking boating activity in areas of high boating activity level and a sufficient AIS coverage. Activity profiles showed that recreational watercraft are concentrated in sea areas within 20 – 30 km from the coastline and in inland waters. In regions of clear seasonal variation, the boating activity level is at its highest during the warmest season of the year. However, possible monsoon and storm seasons might affect the activity profile. Boating is most frequent during the day time. In coastal areas, these results could be used to generate distribution of the boating activity based on the locations of leisure marinas. For inland waters, further studies are needed to estimate the range of the boating activity. More stringent legislation on the engine emissions and on the accepted chemicals in antifouling paints would reduce the responsibility of the boater. More attention should be paid to environmental impacts of boating especially in areas of high boating activity.

Keywords recreational watercraft, emissions, AIS, boating

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Tiivistelmä

Maaliikenteeseen verrattuna meriliikenteen ympäristövaikutusten säätely on kehittynyt hitaasti. Viimeisten vuosikymmenten aikana meriliikenteen kestävyys on herättänyt keskustelua, mutta päästörajoitukset ja -inventaariot ovat keskittyneet vain kaupallisiin aluksiin. Huviveneistä saatavilla olevan tiedon vähäisyys on oletettavasti pääasiallinen syy tähän. Tämän diplomityön tavoitteena oli tunnistaa veneilyn tärkeimmät päästölähteet sekä mahdolliset veneilyaktiivisuuden seurantamenetelmät. Maailmanlaajuisen AIS – aineiston avulla pyrittiin muodostamaan huviveneiden maantieteelliset sekä ajalliset aktivisuusprofiilit. Kirjallisuuden mukaan merkittävimpiä ilmapäästöjä ovat haihtuvat hiilivedyt, hiilimonoksidi, typen oksidit, pienhiukkaset ja hiilidioksidi. Ilmanlaatuun vaikuttavia päästöjä voidaan pitää kasvihuonekaasuja merkityksellisimpinä, sillä huviveneiden osuus maailmanlaajuisista kasvihuonekaasujen päästöistä on arvioitu pieneksi. Vesipäästöistä merkittävimmpiä ovat hiilivedyt, myrkkymaalit ja jätevesi. Päästöjen suuruus vaihtelee riippuen sekä moottorin, että veneen ominaisuuksista, mutta myös veneilijän tekemistä valinnoista ja käyttäytymisestä. Huviveneiden tunnistamiseksi AIS – datasta kehitettiin algoritmi, joka perustuu nykyiseen tietämykseen huviveneiden käytöstä. Tunnistettujen huviveneiden aktiivisuuden perusteella muodostettiin aktivisuusprofiilit. Tulosten perusteella voidaan sanoa, että AIS – aineiston käyttäminen veneiden seuraamiseen on mahdollista alueilla, joilla veneitä liikkuu paljon ja tarpeeksi useassa veneessä on käytössä AIS. Aktiivisuusprofiilien perusteella huviveneet ovat keskittyneet merialueille 20 – 30 km säteellä rannikosta ja sisävesialueille. Alueilla, joilla on selkeät vuodenajat, veneilykausi keskittyy vuoden lämpimimpään aikaan. Mahdolliset monsuunit ja myrskykaudet voivat vaikuttaa aktiivisuuden jakaumaan. Veneily keskittyy pääosin päiväsaikaan. Rannikkoalueilla tulosten avulla on mahdollista muodostaa veneilyaktiivisuuden jakauma perustuen venesatamien sijainteihin. Veneiden käyttäytymisestä sisävesillä tarvitaan sen sijaan vielä lisää tutkimustietoa. Venemoottorien päästöjen ja myrkkymaalien käytön vähäinen sääntely johtaa siihen, että veneilyn ympäristöystävällisyydestä huolehtiminen on pääosin veneilijän vastuulla. Veneiden ympäristövaikutuksiin tulisi kiinnittää enemmän huomiota varsinkin alueilla, joilla veneitä liikkuu runsaasti.

Avainsanat huvivene, päästöt, AIS, veneily

Preface

This thesis was done for the Finnish Meteorological Institute where I had been working as a trainee beforehand. Therefore, the thesis is not only finalising my studies, but also the experience I gained as a trainee. I am most thankful for the FMI for granting me this opportunity. I want to thank my advisor PhD Jukka-Pekka Jalkanen and supervisor prof. Jaana Sorvari who have provided valuable advices and guidance for writing the thesis. I'm also grateful for all my colleagues at the FMI for supporting and encouraging me during this project.

To all my fellow students, thank you for sharing the highs and lows of the student life. I'm also grateful for my other friends and family. This would not have been possible without your support.

Helsinki, 29.7.2019

Elisa Majamäki

Contents

Symbols and abbreviations

Symbols

d	rad	Distance in radians
D	km	Distance in kilometres
f_{BSFC}	g/kWh	Brake-specific fuel consumption
f_{CO_2}	g/kWh	Carbon dioxide emission rate
f_{HC}	g/kWh	Hydrocarbon emission rate
m_{CO_2}	g/mol	Molar mass of carbon dioxide
m_C	g/mol	Molar mass of carbon
P	kWh	Rated engine power
R	km	Radius of the earth
SV	Litres/cylinder	Swept volume of an engine
w_C	-	Carbon mass fraction of the fuel
φ	rad	Latitude coordinate
λ	rad	Longitude coordinate
$\bar{n}$	-	Geodesic normal vector

Abbreviations

AIS	Automatic Identification System
BSFCC	Brake-Specific Fuel Consumption
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DPSIR framework	Drivers–Pressures–State–Change–Impact–Response framework
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
HC	Hydrocarbon
HNO_3	Nitric Acid
HNO_2	Nitrous Acid
IMO	International Maritime Organisation
LRIT	Long-range Identification and Tracking
MID	Maritime Identification Digits
MMSI	Maritime Mobile Service Identity
MTBE	Methyl-Tert-Butyl Ether
NMSC	Australian National Marine Safety Committee
NO_x	Nitrogen Oxides
N_2O	Nitrous Oxide
OSM	Open Street Map
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
PWC	Personal Watercraft
SAR	Synthetic Aperture Radar
TBT	Tributyltin
USCG	U.S. Coast Guard
UTC	Coordinated Universal Time
VHF	Very High Frequency
VOC	Volatile Organic Compound

1 Introduction

1.1 Background

Concerns about the deterioration in air quality, contamination of the environment and climate change have put pressure on introducing stringent regulations on the emissions of energy and transportation sectors. Compared to land based activities, environmental legislation concerning marine transport sector has developed relatively slowly. Insufficient understanding of the environmental impact of marine vessels and the international nature of the sector have made regulating difficult. (EEA 2013) During the last decades, concern about the sustainability of the marine sector has increased and technological development has enabled the construction of more advanced emission inventories and chemical transport models to evaluate environmental impact of this sector. Regardless of the positive development in estimating maritime emissions, emission inventories and regulations have mainly focused on large commercial vessels, neglecting, or only coarsely estimating, the contribution of smaller recreational watercraft.

The main reason for the low level of attention paid to the recreational watercraft can be assumed to be lack of data. Emission inventories and models often require technical details of vessels and information about vessels' activity that are not available for recreational watercraft (Johansson et al. 2017). Only a limited number of countries have registries for recreational watercraft and therefore, the number and the composition of the boat fleet remain largely unknown. While the activity of large commercial vessels can be continuously tracked down by using Automatic Identification System (AIS) or Long-range Identification and Tracking (LRIT) systems, for recreational watercrafts this is not possible as majority of recreational boats do not carry these equipment (EEA 2013; Johansson et al. 2017).

Considering total atmospheric emissions, the contribution of recreational watercrafts is estimated to be small and therefore uncertainties about emissions generated during recreational boating have not caused significant error in global emission inventories (Johansson et al. 2017; TNO 2004). However, boating activity is strongly seasonal and therefore, environmental impacts in areas of high boating density need to be considered. Moreover, boating is mainly concentrated in coastal areas and freshwater systems, which are often sensitive and largely utilised ecosystems, and located close to the human population. Most significant airborne emissions from boats include volatile hydrocarbons, carbon monoxide, particulate matter, and nitrogen oxides. Emissions to the water may be more significant than emission to the air due to the relatively large wet surface of small boats and engines that emit their exhaust directly underwater. When atmospheric emissions are mainly produced by the engine, emissions to water have also other sources, such as antifouling painting and wastewater. (ECNI 2009; TNO 2004) Emission models can provide information about the range and nature of environmental pressures caused by the source and can be used to evaluate the development of emissions in the future. Therefore, emission models can be considered to be an important tool for policy makers to decide if and to what extent the emissions should be controlled. As it is currently not possible to follow recreational boating activity in real-time, generating average profiles of activity would enable construction of more advanced boating emission models. Different approaches could be applied to achieve this, but available methods are often limited by the lack of data. One possible method is to use the Automatic Identification System (AIS) to study the fraction of recreational boating activity that is visible in the system. AIS messages provide information about the identity, location and speed of the vessel and therefore can be used to monitor the activity of vessels at the sea. Even though majority of the small boats do not currently carry AIS equipment, the number of recreational boats with AIS transceivers is increasing (Jalkanen et al. 2014; RYA 2014). AIS coverage is not yet enough for modelling recreational boat activity in real-time, but existing messages could be used to estimate average activity profiles.

1.2 Scope, objectives and structure

The aim of this thesis was to recognise different sources of emission from the operation of recreational watercraft, discuss different methods for tracking the boating activity and use global AIS dataset for generating the geographical and temporal distributions of the activity of recreational watercraft. Accuracy and limitations of generated activity profiles is discussed and the approach of using AIS data to track the boating activity evaluated and compared to other available methods. Sources of environmental pressures from recreational boating and the current knowledge about boating activity was reviewed on the basis of existing literature. Emissions both to the atmosphere and to water are discussed, including noise emissions. Possible impacts of these emissions on the environment are only briefly considered since they are not in the main scope of the study. Only the operation phase of recreational watercraft was considered and no full lifecycle analysis was conducted. Also, majority of land based activities related to the operation of the watercraft, such as travelling to the harbour or transporting the watercraft, were excluded in the analysis.

The DPSIR (Drivers–Pressures–State–Change–Impact–Response) framework is a method used for describing the interactions between society and the environment. It has been used as a tool for communication between researchers from different fields and between researchers and stakeholders or decision makers. (Svarstad et al. 2008) Figure 1 briefly describes the concept of the DPSIR in the case of recreational boating. Within the scope of this framework, this thesis focuses on environmental pressures caused by recreational watercraft and direct drivers that lead to these pressures. By focusing on these parts, this thesis aims to provide information to support the following steps of the framework.

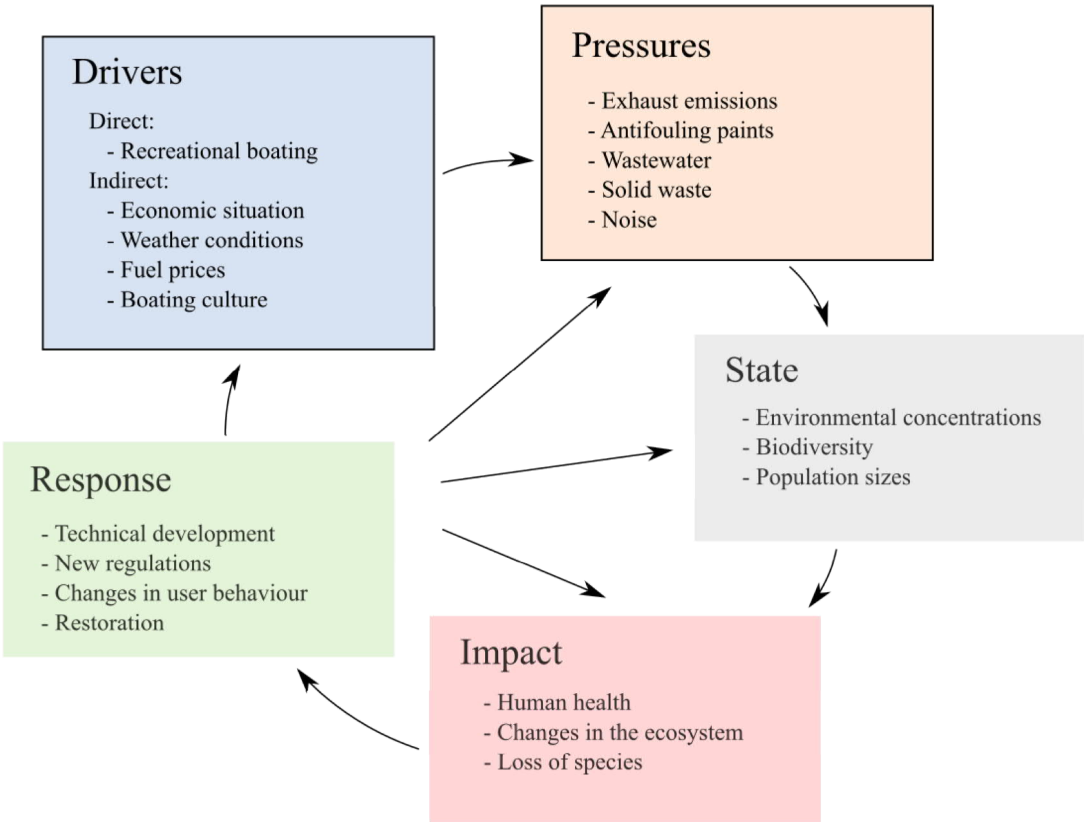


Figure 1: the DPSIR (Drivers–Pressures–State–Change–Impact–Response) framework describing the interactions of recreational boating and the environment. Drivers are changes in the system that trigger pressures (e.g. environmental load) resulting in impact on the environment and therefore, change in the state of it. Responses are actions that aim to prevent or compensate the consequences of these impacts.

AIS dataset was used to estimate geographical and temporal profiles of recreational watercraft activity. Temporal profile aims to reveal the variation in the boating activity level between different months, days and hours of the boating season. Geographical distribution aims to show the travel distance of small boats and how far from a marina the boat activity can be detected. Also, the coverage of AIS network and the share of recreational watercraft fitted with AIS equipment are discussed. Main focus is on the area of European Union, but other regions are also discussed. In particular, this thesis aims to answer the following questions:

- What are the most important sources of environmental pressures caused by recreational boating?
- What is the state-of-art of estimating recreational watercraft emissions?
- How much information about recreational watercraft activity can be obtained from AIS – data?
- What are the temporal and geographical profiles of activity of recreational watercraft according to AIS – data?

This thesis is divided into seven chapters. This chapter describes the motivation and background for the study, and defines the scope and objectives of the thesis. In the second and third chapter, existing literature is reviewed to understand the current state-of-art of tracking recreational watercraft activity and to recognise sources of emissions from recreational boating. The fourth chapter describes the data and the method used in the empirical part of the study. Results of the study are presented in chapter five. These results and findings of the literature review are discussed in chapter six. Finally, main conclusions are presented in chapter seven.

2 Recreational watercraft

2.1 Boat types

European Council Directive 2013/53/EU on recreational craft and personal watercraft defines a recreational craft as *"any watercraft of any type, excluding personal watercraft, intended for sports and leisure purposes of hull length from 2.5 m to 24 m, regardless of the means of propulsion."* This definition for a recreational watercraft is used in this thesis. Additionally, word "boat" is used as a synonym for a recreational watercraft. Personal watercraft (PWC) is defined as *"a watercraft intended for sports and leisure purposes of less than 4 m in hull length which uses a propulsion engine having a water jet pump as its primary source of propulsion and designed to be operated by a person or persons sitting, standing or kneeling on, rather than within the confines of, a hull."*

Recreational watercraft vary in size, mean of propulsion and the purpose of use, but currently it is not feasible to aim to collect technical details of all individual boats. Dividing watercraft into subgroups based on technical characteristics makes it possible to obtain a better understanding of the environmental pressures they may cause. Size and propulsion of the boat affect the rate of emissions generated during the operation, but they can also be used to estimate the intensity and the profile of the use.

Sailing boats are designed to accelerate by using wind and therefore installation of an engine is not necessary. However, a small engine is often installed to provide assistance for manoeuvring and sailing during low wind speeds. Sailing boats without indoor facilities are normally fitted with an outboard engine, but sailing boats with a cabin may also have a relatively powerful inboard engine. (TNO 2004) Sailing boats are typically larger than motorboats and used for travelling longer distances and time periods than other boat types. Sailing boats are more often operated at the sea rather than in inland waters (Trafi 2017; Lagerqvist et al. 2016). Open motorboats are normally used for a limited time period for transportation purposes or for sports, such as water skiing or speeding, but motorboats with a cabin can be used for cruising and longer trips. All engine types are possible in open motorboats. Cabin motorboats are normally fitted with an inboard engine, but in smaller units also outboard engines occur. (TNO 2004)

Personal watercraft are normally fitted with an inboard gasoline engine, which powers the water jet used for propulsion. PWCs tend to be driven at higher speeds than recreational boats and can also be operated in wider range of environments, including shallow waters that might be unreachable by a boat (Burger and Leonard 2000). The data of the PWC fleet is not comprehensive and for many regions, the number of PWCs is unknown. In regions where the number of PWC's has been reported, the share of PWCs in the recreational watercraft fleet varies from 1.7 % up to 20 % (ICOMIA 2017).

Figure 2 shows estimated numbers of different boat types in different parts of the world. Largest known recreational watercraft fleets are in Canada, USA and Europe, rest of the world accounting for less than 7 % of recreational watercraft. Availability of the data for recreational watercraft varies and therefore these numbers may be highly uncertain. Many countries have no estimations of the number of recreational watercraft and therefore the contribution of some regions is missing from the numbers presented in the figure 2. Proportions of different boat types are not known in all countries, but the existing data implicates that an outboard motorboat is the most common boat type. Some boating surveys conducted in Northern Europe and USA show that the most common type of a recreational watercraft is an outboard motorboat of a hull length of 7 metres or less (Trafi 2017; Lagerqvist et al. 2016; USCG 2012).

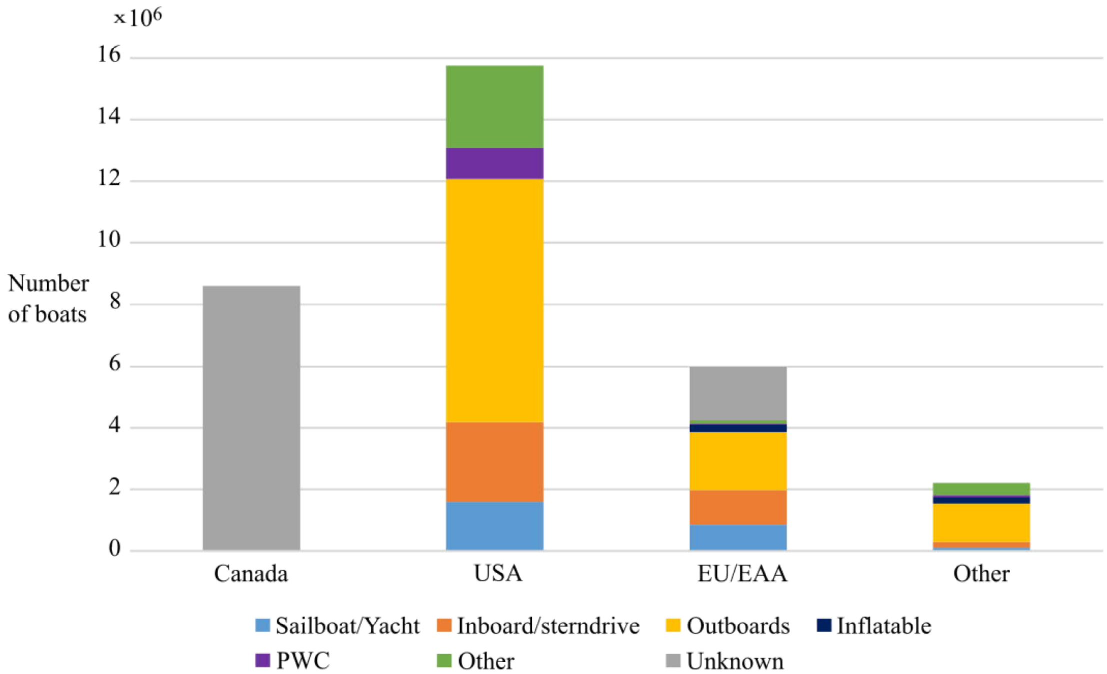


Figure 2: Number of different recreational watercraft types used in different countries(ICOMIA 2017).

2.2 Engine types

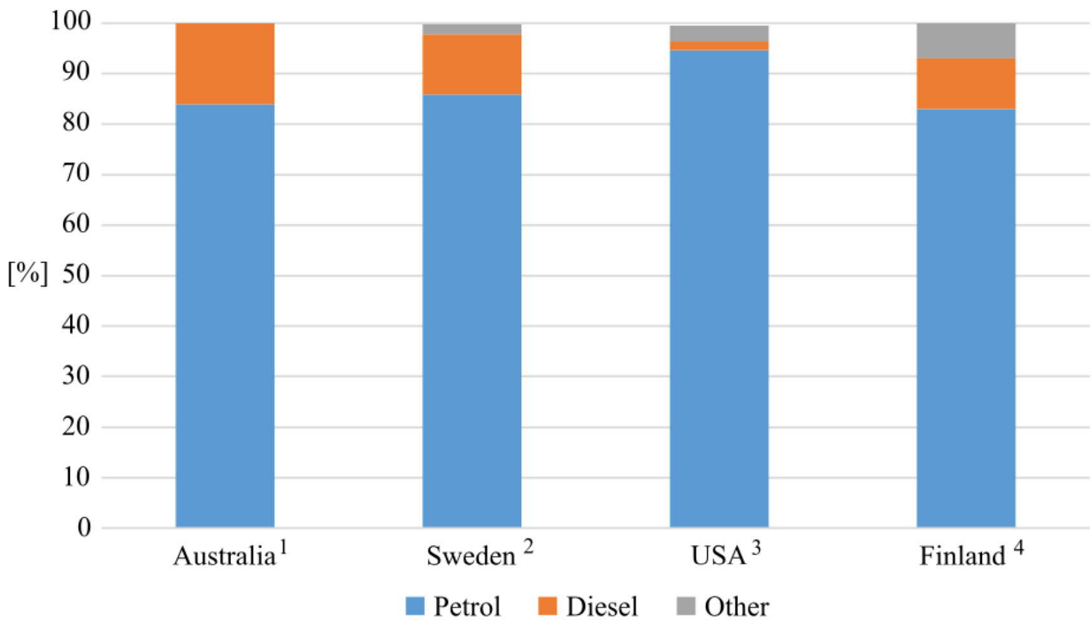
Recreational marine engines are generally categorised based on the installation of the engine. Outboard engines are placed outside of the hull when inboard engines are installed in an engine compartment inside the boat. Outboard engines are often compact and portable and therefore, might not be left permanently attached to the boat outside the operation time. These engines tend to be technologically simple, easy to maintain and cheaper than inboard engines. Due to size and weight limitations of outboard motors, two-stroke engines are preferred over four-stroke engines. Inboard engines are installed inside the hull by the manufacturer and therefore the mobility of the engine is not a concern. However, in the case of a cabin boat, the available inner space is valuable and therefore the manufacturers prefer compact engines also in the case of an inboard unit. Sterndrive can be considered to be a combination of outboard and inboard engines as the drive unit is outside the hull but the remaining part of the engine is mounted inboard. (TNO 2004)

There are two main types of internal combustion engines in the boat market: two-stroke and four-stroke engines. Naming of these two types is based on the number of strokes of the piston needed to complete the crankshaft revolution and the four processes of intake, compression, power and exhaust. Two-stroke engine completes the crankshaft revolution in two piston strokes while a four-stroke engine completes the cycle in four piston strokes and therefore all four stages are performed during separated strokes. Two-stroke generally have lower costs and a more reliable operating behaviour than four-stroke engines. Also, the power output is higher when compared to the size and weight of the engine. However, as the power and exhaust stroke are not separated, a small fraction of fuel might be released to the environment unburned or only partly combusted. Moreover, two-stroke engines rarely have a separate lubrication system and the lubrication oil is mixed within the fuel. This increases hydrocarbon emissions generated by the engine and might also decrease the lifespan of the engine due to the lack of proper lubrication system. Four-stroke engines tend to have a higher fuel efficiency than two-stroke engines and due to a proper lubrication system, four-stroke engines are generally longer-lasting. However, Four-stroke engines have higher production costs than two-stroke engines and are heavier and larger in comparison to the power output. (Kelly 2004)

Two different methods of ignition are used based on the fuel type of the engine. In spark ignition (SI) engines, also known as petrol engines, the mixture of air and fuel is ignited by a spark. In compression ignition (CI) engines, also known as diesel engines, the heat generated during the compression of the air is used to ignite the fuel which is injected to the combustion chamber. (Haapakoski 2016) Outboard engines are generally spark ignition engines due to the weight and size limitations. Inboard engines can be both spark ignition engines and compression ignition engines. (TNO 2004)

2.3 Fuel types and consumption

Recreational watercraft generally use diesel and petrol fuels similar to the road transport, but some electric boats and boats using alternative fuels exist. Estimating the total fuel consumption of recreational watercraft is challenging as the fuel can be purchased from any filling station and it can be difficult to identify the fraction of the fuel consumed by recreational watercraft. Some national boating surveys have tried to estimate the share and the amount of different fuels consumed by boats (figure 3). The high number of petrol engines is due to the large number of small motorboats, which are typically fitted with an outboard petrol engine. Number of engines using certain fuel might not accurately represent the total amount of fuel consumed as the intensity of the operation and the fuel consumption rate of the engine affect the amount of consumed fuel. Larger seagoing vessels tend to have diesel engines, and according to some national boating surveys (Lagerqvist et al. 2016; NMSC 2009; Trafi 2017; USCG 2011), they are also used more often and for longer time periods than smaller motorboats. For example, a national boating survey by the Finnish Transport Safety Agency estimated that the volumes of petrol and diesel fuels used by recreational watercraft in Finland were approximately equal although the number of petrol engines is significantly higher (Trafi 2017).



(1) NMSC 2009
(2) Lagerqvist et al. 2016
(3) USCG 2011
(4) Trafi 2017

Figure 3: Fuel types used by recreational watercraft engines in some countries.

EEA (2016) listed fuel consumption rates for different recreational marine engines. A two-stroke outboard engine was estimated to use 791 g/kWh of fuel, four-stroke engine 426 g/kWh of fuel and a diesel engine a range of 275 – 285 g/kWh depending on the engine power. A study by the Netherlands national water boards (2008) used fuel consumption rates based on the type of the recreation watercraft and the operation time. Fuel consumption was estimated to be 1.95 kg/h for an open sailboat, 1.52 kg/h for an open motorboat, 5.09 kg/h for an open speedboat, 2.4 kg/h for a cabin sailboat and 3.74 kg/h for a cabin motorboat.

2.4 Activity

To construct a realistic emissions model, data on the number and the type of recreational watercraft is not enough, but also spatial and temporal activity profiles need to be known at least to some extent. Luckily, detection of non-commercial boats is not only in the interest of environmental researchers, but also a concern of marine traffic management and coastal security and therefore, some attempts to monitor the activity have already been made.

2.4.1 Automatic Identification System (AIS)

The automatic identification system (AIS) is a ship tracking system primarily designed for collision avoidance and to enable identification of a vessel, which is not possible with commonly used radar system. AIS transceivers automatically transmit information about the vessel, its position and dynamics. The broadcasted information depends on the capacity of the transceiver and the extent of manual input data given by the user. Messages are sent via a Very high frequency (VHF) transmitter at a frequency depending on the type of the transceiver and the operation mode of the vessel. AIS messages are primary used for collision avoidance, but also for safety and rescue purposes, marine traffic control and research. (Robards et al. 2016)

International Maritime Organisation (IMO) mandates all passenger ships, ships of 300 gross tonnage or more engaged on international voyages and cargo ships of 500 gross tonnage or more not engaged on international voyages to carry AIS. Additionally, there are national and regional requirements for the use of AIS system. European Commission Directive 2011/15/EU requires all fishing vessels of overall length of 15 metres or more to be fitted with AIS. On the waters of the USA, all commercial vessels of overall length of 19.8 metres or more, towing vessels of overall length more than 7.9 metres and 600 horsepower shall use AIS (46 U.S. Code § 70114). Generally, recreational watercraft are not obligated to carry AIS, but there are some exceptions. In Singapore, all power driven pleasure craft are required to be fitted with AIS (MPA 2015). Also, in Phuket, a popular travelling destination in Thailand, all foreign boats shall carry AIS (Phuket News 2014). In Flanders, Belgium, and the Netherlands instead of regulating the use of AIS, a subsidy program has been used to encourage boaters to install AIS on-board. The subsidy for AIS installation has been available for all boaters under any flag state who can demonstrate that they use waterways in the Netherlands or Fleming. (European Commission 2014)

AIS messages can be coarsely divided into two classes depending on the transmitter technology: Class B and Class A. Class A AIS is more powerful than Class B and therefore it is generally required to be carried on IMO regulated vessels. Class B AIS is more used on those vessels, which are not required to carry AIS, but do so voluntarily. All message types contain Maritime Mobile Service Identity (MMSI) code of the vessel, the coordinates of the location, speed and course. Higher level messages can also show navigational status, destination and ETA, and also technical information such as vessel type and dimensions. Typical range of AIS to a surface receiver is 13 – 39 km depending on the power of the transceiver, but also on other parameters, such as topography and atmospheric conditions. Due to a relatively low reach of AIS signal, land-based receivers only cover the coastline, and to obtain a global view of marine traffic, satellite-based AIS receivers need to be used. (Robards et al. 2016) The share of the marine traffic covered by AIS is unknown but there have been some attempts to estimate the coverage. Barco et al. (2012) compared radar and AIS data in the Chesapeake Bay Ocean approach of the USA and discovered that the AIS data represented 49.7 % of observed vessels.

AIS messages sent by a vessel might contain erroneous information and therefore the AIS data is not completely reliable. This can be caused by technical failures or human error, but there is also evidence of intentional misuse of AIS. Some fishing vessels have been reported to turn off the AIS at sea, which might indicate that these vessels were fishing in protected areas or in waters where they are not authorised to fish (Malarky and Lowell 2018). In some areas, particularly in the East China Sea, some fishing nets have been fitted with AIS to protect them from possible collision with a vessel (Kovary 2018). These nets will appear in the AIS data as ships and therefore falsely contribute to the vessel activity in the area. There are also some areas where switching off the AIS is allowed due to safety concerns, such as pirates.

As mentioned previously in the chapter 1.1, majority of recreational watercraft are not equipped with an AIS, but those that are can be studied to obtain information about boating. AIS messages have been used to estimate temporal variation of small boat activity in the Baltic Sea (SHEBA 2016) and the boating density at the coastline of the United Kingdom (RYA 2016). Most of the boating surveys have not included questions about the use of AIS receivers and transmitters on recreational watercraft and therefore, the coverage of AIS in this part of the fleet is widely unknown. A survey by RYA (2014) aimed to reveal the number and distribution of recreational boaters using AIS equipment in the UK. According to the results, 37 % of boaters were both transmitting and receiving AIS messages and 33 % only receiving, leaving a share of 30 % of boaters not using any AIS equipment. These rates of AIS usage are larger than previously estimated and it is stated that results of the survey are most likely biased as boaters using AIS equipment have been more active answering the AIS related survey. Sailing boats were more represented as 86 % of AIS using vessels were sailing boats and only 14 % motorboats. Majority, 74 % of boaters with AIS equipment, were boating at the coast or offshore. Also, analysis of longer time period shows that the number of AIS transmitters in recreational watercraft has been increasing during monitored years 2011 – 2013.

2.4.2 Other methods for estimating the level of activity

Some countries maintain a national registry for recreational watercraft, but the total number of boats still remains largely unknown. In Finland, all recreational watercraft with a hull length over 5.5 metres or with an engine power over 15 kW must be registered by the boat owner (laki 6.6.2014/424). In Sweden, all vessels with a hull length of at least 12 metres or over and the maximum breadth of at least 4 metres must be registered, unless they are owned by the government (Sjölag 1994:1009). In the USA, the requirements for the registration of boats vary between different states. In 2011 it was estimated that 57 % of boats in the USA have been registered, but there are significant differences in registration rates between the states. (USCG 2011)

Previously, geographical distribution of recreational watercraft has been mainly estimated based on results of the national surveys, but other possible methods have also been discussed. Conducting a phone or a web survey is relatively easy as it does not require special equipment or technology, but the number and quality of answers depends on the activity of the boaters participating in the survey. Moreover, the collected data might not be reliable as participants might intentionally or unintentionally give incorrect or misleading answers. However, with a survey it is possible to gather information that other methods might not be able to provide, such as data about wastewater or solid waste management in the boat, or about the use of antifouling paints. (USCG 2011)

Crisp (2004) describes the state-of-the-art in ship detection by synthetic aperture radar (SAR) imagery. SAR images are formed based on the reflectivity of the scene and therefore boats constructed of metal tend to be detectable in these images. Also, boat wakes are detectable and can be used to track the boating activity. Often watercraft are not the only reflecting objects in the SAR image and therefore, it is important to be able to identify them from other bright targets. Land masking can be used to avoid false alarms caused by permanent objects, such as land areas. However, land masking will not remove the possibility of false detections caused by temporal objects, such as waves or airplanes. Especially when detecting smallest fraction of watercraft, identifying a boat from the background noise of the image is challenging and the possibility of false detection is high. SAR images have been used to detect small boats in several studies (Silva and Greidanus 2011b; Silva and Greidanus 2011a; Máttyus 2013), but the focus has been in safety and traffic control purposes instead of studying the boating activity.

Optical image taken from a satellite or an airplane can also be used for detecting boats, but unlike SAR imagery, the quality of these images might be affected for example by the disturbance caused by the climate. However, optical images can reveal also boats made of wood or fiberglass, which are difficult to detect in SAR images due to low reflectivity of these materials. Optical images can also provide high levels of detail if the resolution of the image is high enough and therefore, more information can be obtained than from SAR images. (Willhauck et al. 2005) Satellite images have been used by the Sustainable Shipping and Environment of the Baltic Sea region (SHEBA) to find locations of small boat marinas at the coastline and to estimate the number of available mooring places (SHEBA 2016). Following figure 4 shows an example of a satellite image that can be used to calculate available mooring places in a recreational boat marina.

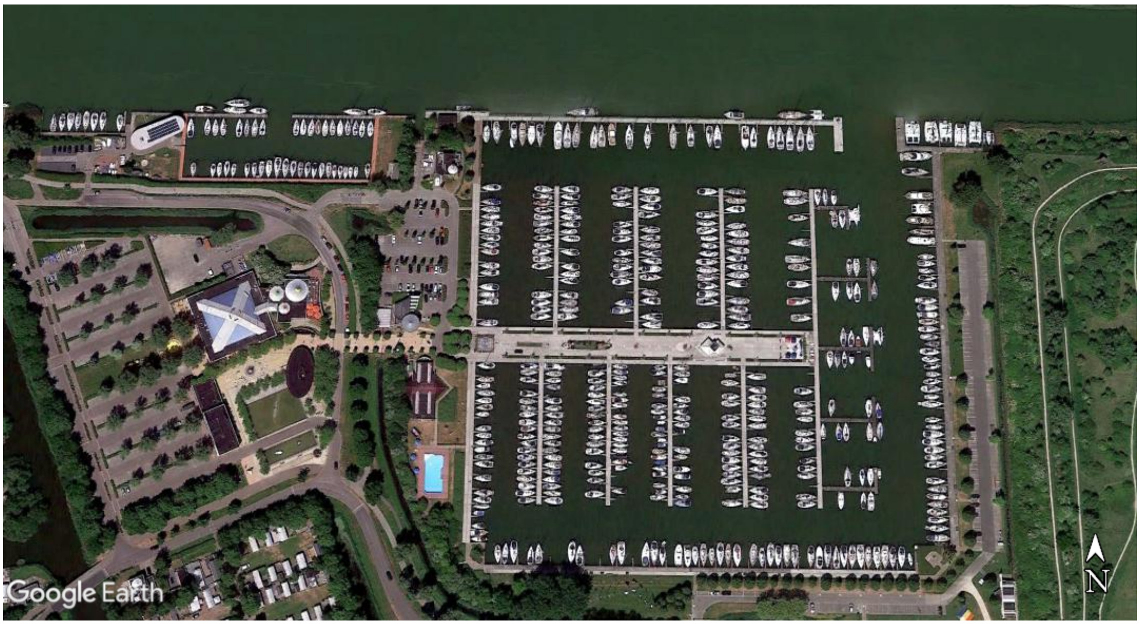


Figure 4: Example of a Google Earth satellite image that can be used to calculate available boat mooring places in a marina.

While data about the boating activity is often unavailable, Search and Rescue (SAR) data related to boating is more often reported at least on the national level. Assuming that the number of boating accidents correlates with the intensity of boating activity, SAR statistics could be used to obtain information about boat usage. Of course, this method would be affected by other factors, such as the weather and navigation conditions. Jin et al. (2002) modelled the probability of fishing vessel accidents and mapped the number of accidents related to fishing vessels. Similar approach could be used to study accidents related to recreational watercraft and the results could give some perspective about the range of the boating activity.

2.4.3 Geographical distribution

Lagerqvist et al. (2016) conducted a boating survey to provide information about the current state of recreational boating in Sweden. Boaters were asked to estimate the total boating distance they covered during the boating season in 2015. Figure 5 shows results of this survey. The activity of different boat types varies significantly as majority of boats with a 10 hp engine or smaller travelled less than 25 nautical miles (46.3 km) while almost 30 % of sailboats with cabin travelled more than 500 nautical miles (926 km) during the season. However, these results might contain high uncertainties as many participants (42 %) were not able to estimate the total distance travelled.

A survey by the National Marine Safety Committee (NMSC) on national boating usage in Australia included question about how far from the shore boaters travel when operating in open waters. Figure 5 shows answers to this question. Results showed a correlation between boat length and the distance the boat travelled from the coastline. A significant share of the boats staying near the shore were the smallest boats (maximum length of 5 metres) while larger boats more often travelled a long distance offshore. (NMSC 2009)

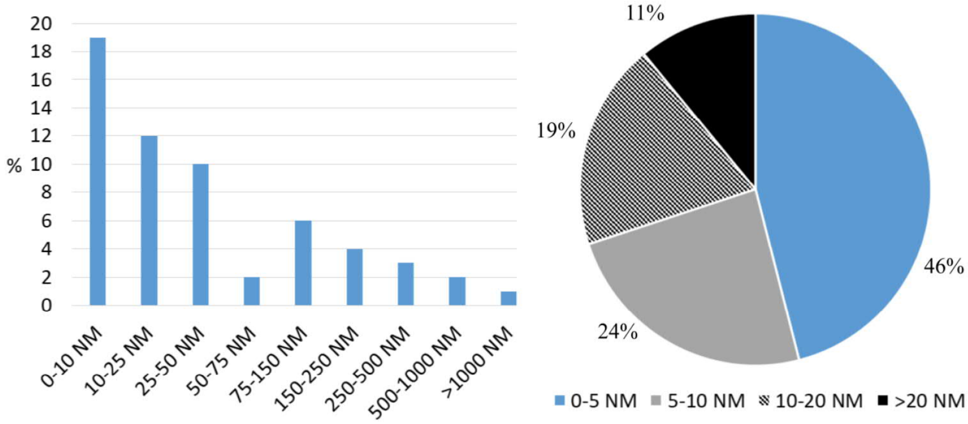


Figure 5: Total distance travelled by a boat annually (a) and distance from the shore visited by a boat (b) (Lagerqvist et al. 2016; NMSC 2009).

It can be assumed that the recreational watercraft fleet is not homogeneously distributed in different areas. A survey by Lagerqvist et al. (2016) showed that 25 % of the boat population in Sweden is active in inland waters. A similar survey in Finland indicates that 58 % of the Finnish boat fleet is active in inland waters. Results of a survey conducted in Finland also showed that smaller watercraft are more likely to be used in inland waters when larger boats tend to be active at the coast. (Trafi 2017) These numbers are most likely lower in countries with less inland waterbodies than in Sweden and Finland. ECNI (2006) proposed that in inland waterways, 90 % of the recreational watercraft are motorboats with a hull length of 7.5 metres or less and 10 % motorboats with a hull length of more than 7.5 metres. In lakes, the recreational watercraft fleet was estimated to consist of 52 % of smaller motorboats, 21 % of larger motorboats, 22 % of sail boats and 5 % of PWCs. In coastal marinas, 68 % of watercrafts were proposed to be small motorboats, 9 % larger motorboats, 19 % sail boats and 4 % PWCs. However, it is stated that the given share of the sail boats at the coastal marina is most likely lower than in reality.

2.4.4 Temporal activity profile

Study by Lagerqvist et al. (2016) revealed that the most common purpose of use of a recreational boat in Sweden is a day trip or a fishing trip. Approximately 10 % of boaters use their boat for transportation purposes as well as 10 % use the boat for longer trips with an overnight stay. A clear majority of boating trips are conducted between May and September and only a small fraction of boaters reported to be active during the winter season. Similar results were presented in a boating survey conducted by Trafi (2017) in Finland. However, more detailed analysis showed that there is large variation between purposes of use of different boat types. Smaller motorboats are almost entirely used for day trips or transportation when sailboats are often used for trips of several days.

A survey by the NMSC in Australia showed that boating is strongly concentrated on the summer holiday season. During the winter season, only 30 % of respondents went boating while during the summer holiday season the boating participation rate increased up to 95 %. Also, the weekly variation (figure 6) of the operation was studied and the results supported the assumption that boating activity is highest during the weekend and lower during the week. According to the study, the most popular time of the day for boating is between 6 am and 2 pm. Boating activity during different times of the day are shown in figure 6. The most common frequency of boating was 2 – 3 times a month accounting for 39 % of responses, followed by “once a week” and “once a month” answers which both accounted for approximately 20 % of responses. The most common duration of a single trip was 3 – 5 hours accounting for 47 % of responses and the second most common 6 – 10 hours accounting for 38 % of responses. (NMSC 2009)

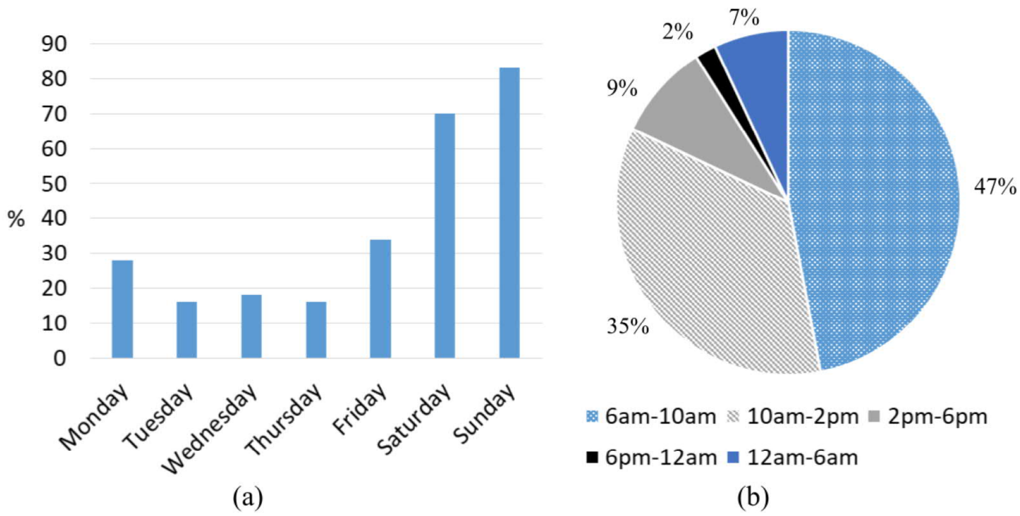


Figure 6: Share of boaters participating in the boating during the week (a) and day (b) (NMSC 2009).

U.S. Coast Guard (USCG) has conducted boating surveys for different regions of the USA. A survey by USCG (2011) revealed that in 2011, the overall proportion of boats used in the USA during the year was 65.5 %. On average, boats were used for 17 days and the average duration of one boat trip was 4.5 hours. A later survey by USCG (2012) showed that in 2012 the average number of boating days was 11.3 during the year and the average duration of a boating trip was 5.7 hours. Comparison of boating activity between different regions of U.S. shows that the number of boating hours in a year is highest in the South and lowest in the West. In the North East, New York and Pennsylvania account for largest proportions of total boating hours. In the South, the State of Florida is the largest hot spot for boating, and in the West the State of California. In the Midwest Michigan and Wisconsin have the highest numbers of boating hours.

3 Environmental pressures

3.1 Emissions to the atmosphere

Most significant airborne emissions from recreational boating include volatile hydrocarbons, carbon monoxide, particulate matter, nitrogen oxides and ozone. The exhaust can be emitted directly to the air or below the water surface. However, a major part of the exhaust is in a gaseous form and therefore will be released into the atmosphere even if the exhaust outlet is located underwater.

3.1.1 Nitrogen oxides (NO_x)

Nitrogen oxides (NO_x) are produced in the oxidation of nitrogen in the combustion chamber. The primary source of nitrogen is the organic nitrogen in the liquid fuel as it is more easily oxidised than the free nitrogen in the air. Therefore, the nitrogen content in the fuel is a critical parameter affecting the level of nitrogen oxide emissions. The reaction between nitrogen in the air and oxygen is occurring only under certain conditions, favoured at high temperatures and optimal air/fuel ratios. The primary product from the reaction between nitrogen and oxygen is nitric oxide (NO) of which a fraction up to 10 % will further react mainly to nitrogen dioxide (NO_2) and a small amount to nitrous oxide (N_2O). (Kristenen 2015)

Nitrogen oxides can either deplete or enhance the ozone concentration in the atmosphere. Being hit with a photon of ionising radiation, such as sunlight, NO_2 can react with an oxygen molecule and create a new ozone molecule and a NO molecule. As NO molecule can again react with oxygen to create a new NO_2 molecule, one NO_2 molecule can create a new ozone molecule multiple times. Tropospheric ozone is the constituent of photogenic smog and causes a threat for human health by irritating and damaging the respiratory system. N_2O is depleting ozone both in the troposphere and in the stratosphere. Nitrogen oxides dissolve in water and they can form nitric acid (HNO_3) or nitrous acid (HNO_2) and therefore, attribute to the acid rain that can damage both natural environment and properties or infrastructure. (EPA 1999)

3.1.2 Particulate matter (PM)

Particulate matter occurs naturally in the atmosphere due to volcanic eruptions, dust storms and fires, but human activities, such as combustion engines, increase the particulate concentration in the air. Particulate matter can be formed directly in the combustion chamber and then be emitted to the air within the exhaust gas, but it can also be formed in reactions of other pollutants in the atmosphere, such as nitrogen oxides, sulphur dioxide and Volatile Organic Compounds (VOC). (WHO 2013) The chemical composition and size of particles vary by source and location. The carbon core of the particle can be coated with organic compounds, such as hydrocarbons, and with inorganic compounds, such as sulphates and nitrates. Particles might also contain other substances, for example metals, endotoxins and microbial compounds. (Myung and Park 2011; WHO 2013)

The final fate of the particle depends on its aerodynamic diameter. If inhaled, particles with an aerodynamic diameter of 2.5 – 10 μm (PM_10) mainly deposit in the upper respiratory tract when particles with a diameter less than 2.5 μm ($PM_(2.5)$) can also reach lung alveoli (Kampa and Castanas 2007). Moreover, the diameter affects the time a particle can stay in the atmosphere; smallest particles can persist for days or weeks and thus travel long distances. Particulate matter can increase the risk of mortality from cardiovascular and respiratory diseases and lung cancer. Moreover there is evidence of particulate matter affecting the lung development and therefore, the exposure is more harmful for children. (WHO 2013)

3.1.3 Carbon monoxide (CO)

As a poorly soluble compound, at least 80 % of carbon monoxide in the exhaust will be released into the atmosphere even if the exhaust is discharged underwater (TNO 2004). Carbon monoxide is produced in the incomplete combustion of fuels containing carbon and typically gasoline engines produce larger carbon monoxide emissions than diesel engines (Elliott et al. 1955). Produced CO gas is colourless, odourless and tasteless and therefore hard to detect without proper equipment. When inhaled, CO binds to haemoglobin and therefore it impairs the ability of the blood to transport oxygen in the circulatory system. High carbon monoxide emissions on-board can cause an acute poisoning with symptoms such as headache, tinnitus, nausea, vomiting and weakness. In most severe cases, this poisoning can lead to loss of consciousness, coma and eventually death. Unlike the acute effects of CO, effects of a long-term exposure to low level concentrations are less known. However, there is evidence that already low concentrations cause symptoms for patients with coronary artery or heart disease. Also, increases in ambient CO concentrations have been connected to increase in heart diseases, congestive heart failures and deaths by cardiopulmonary illnesses. (NRC 2009)

3.1.4 Volatile organic compound (VOC)

Hydrocarbon emissions that discharge into the water tend to rapidly travel to the water surface forming a film with a large surface area and therefore, volatile hydrocarbon components evaporate fast. Approximately 60 % of the hydrocarbons discharged to the water will evaporate to the atmosphere immediately after being released. The fraction of VOC retained in the water phase will continue to evaporate. (TNO 2004) VOC concentrations in the air can cause health impacts, such as irritation of respiratory organs and headache. Moreover, some volatile organic compounds are carcinogenic. (EPA 2017) VOCs can also contribute to the formation of tropospheric ozone and particulate matter (NIWA 2007; WHO 2013).

3.1.5 Carbon dioxide (CO_2)

Carbon dioxide is one of the main products of the combustion of carbon containing fuels. The stored carbon is almost entirely emitted as carbon dioxide and therefore the carbon content of the fuel is the most important factor controlling CO_2 emissions from the engine. Therefore, unlike some other pollutant, carbon dioxide emissions cannot be controlled by improving the combustion efficiency, but only by reducing the usage of carbon-based fuels. Approximately 65 % of the produced carbon dioxide is immediately released into the atmosphere even if the exhaust gas is discharged underwater. (TNO 2004) Burning fossil fuels increases the level of carbon dioxide concentration in the atmosphere, which contributes to the human induced climate change. Increasing of the atmospheric temperature can lead to impacts, such as the Artic sea ice retreat, changes in precipitation and an increase in intensity of extreme phenomena of the climate. Moreover, the fraction of CO_2 emissions that is mixed into the ocean might change the ocean chemistry. (Solomon et al. 2009)

3.2 Emissions to water

A fraction of gaseous exhaust from the engine can be dissolved into the water, especially if the exhaust outlet is located below the water surface. Moreover, when considering emissions into water, there are several other emission sources in addition to the engine exhaust, such as antifouling paints and wastewater.

3.2.1 Hydrocarbons (HC)

Hydrocarbon emissions are generated due to incomplete combustion of the fuel. Hydrocarbons are also found in petroleum products and motor oils, and therefore can be released to the environment during the fuelling of a boat or within engine exhaust cooling water or bilge water discharges. (Magnusson et al. 2018; ECNI 2009) Two-stroke petrol engines have been considered to be a more significant source of hydrocarbon emissions than other recreational marine engines due to the low efficiency of the engine type. However, according to the manufacturers, the fuel efficiency of new two-stroke engines has improved significantly. (GESAMP 2007) Rice et al. (2008) studied hydrocarbon levels in Auke Lake in southeast Alaska for five summers and revealed both temporal and spatial correlation between the activity of recreational watercraft with a two-stroke engine and hydrocarbon levels in the Lake. Also Bannan et al. (2000) and Mastran et al. (1994) found a correlation between boating activity and increased hydrocarbon levels in surface waters, of which later also revealed a correlation in sediment PAH concentration and boating activity. A study by GESAMP (2007) estimated that small watercraft contribute to 4 % of average annual oil inputs to the sea. It is stated that although the data for small boat activity is limited, and the result might not be accurate, more attention should be given for this emission source.

Hydrocarbons are a group of a wide range of different compounds and therefore, the possible effects on the environment and human health also vary. According to NIWA (2007), the main hydrocarbon emissions from boating to the water are benzene, toluene, ethyl benzene, xylene, methyl-t-butyl ether (MTBE) and polycyclic aromatic hydrocarbons (PAHs). Benzene, toluene, ethyl benzene and xylene correspond to

20 – 50 % of petrol and therefore, concentrations in the surface water can be high immediately after a boat has passed by. However, these chemicals are highly volatile and are therefore rapidly evaporated from the water. PAHs are generally poorly soluble in water and poorly degradable, but due to a high affinity for particles and organic matter, they will be easily absorbed to the bottom sediments (Hylland 2006). Some smaller PAHs are more water soluble and therefore more bioavailable and can cause an acute threat to aquatic organisms (NIWA 2007). As PAHs are relatively easily metabolised they are not biomagnified in the food chain and the main pathway of exposure is taking up the contaminant directly from water. The most extensively studied effect of PAHs is carcinogenicity, but other effects have also been discovered. PAHs have been found to cause oxidative stress, and they disturb the immune system, endocrine regulation and the development. (Hylland 2006). MTBE is added to fuel in some areas to increase the octane value of the fuel. Unlike many other hydrocarbons, MTBE is soluble to water and therefore, it is more bioavailable. High concentrations of MTBE are acutely toxic and lower concentrations can cause taste and odour problems in the water. (NIWA 2007)

3.2.2 Black and grey water

Black water, or sewage, contains high concentrations of nutrients, organic matter and suspended solids and may also contain pathogens and medicine residues. Discharging untreated sewage to the environment can cause a variety of environmental problems, such as eutrophication and deoxygenation, and can also be a health hazard by introducing pathogens into the surrounding water. Grey water refers to water generated from hygiene and cleaning activities and therefore it mainly contains salts, fats and possibly chemicals. Grey water typically does not contribute to eutrophication or health hazards in the same way as black water. However, grey water can contain hazardous compounds if toxic chemicals are used on-board for example in a form of detergents. (ECNI 2009) The level of the health risk caused by discharging the wastewater from boat to the water depends on the location where this action takes place; near the coastline or areas with any water related activities, such as swimming or water-skiing, the health risk is higher than at the open sea.

For the smallest boats, which are used mainly for transportation over small distances, using onshore toilet facilities is more common than using on-board systems. Different types of on-board wastewater systems are available for recreational boats with enough inner space for such facilities. The simplest toilet types discharge the content directly into the water without capability to store it. Similar systems exist with a holding tank, which allows the waste to be discharged at chosen time and location. Holding tanks of more advanced toilet types can be emptied through pump-out hose at a marina providing services for the dispose of wastewater. Additionally, there are chemical and composting toilets, which aim at some level of treatment already on-board. (Kavanagh 2005)

3.2.3 Antifouling paints

Antifouling paints are used on the surface of the boat hull to avoid biofouling: unwanted growth of aquatic organisms. Biofouling of the boat hull has negative economic and environmental impacts as the increase in biomass on the hulls surface increases the drag. This increases the fuel consumption and therefore, also the costs and emissions generated during the operation of the boat. Biofouling can also cause additional corrosion of the watercraft and affect the manoeuvrability. Moreover, in case of longer trips, organisms attached to the hull might travel to new habitats and pose a threat to the local ecosystem. (Bighiu 2017) Chemicals in antifouling paints are designed to slowly leach into the surrounding water. Moreover, particles containing antifouling paint may be released to the environment due to maintenance work, cleaning of the boat hull and from abandoned boat wrecks. Release rate of the contaminant is specific to the type of an antifouling product. Leaching rate data are scarce, and has mainly been generated in laboratory conditions and therefore, might not represent the actual leaching in the environment. (Thomas and Brooks 2010)

There is a wide range of different chemicals which are used as antifouling paints and the toxicity and bioavailability of these chemicals vary. After the use of Tributyltin (TBT) was banned globally in 2008, it has mainly been replaced with copper, zinc and organic biocides. Both copper and zinc are naturally found in the environment, but in high concentrations, they become toxic. Toxicity of copper depends on the form it occurs in the environment; copper is most bioavailable as free copper ions, less available in inorganic form and to large extent not bioavailable when bound to organic matter. Copper tends to adsorb to suspended particulate matter and is therefore easily accumulated in the sediment. (Thomas and Brooks 2010) Several different biocides are used to boost the efficiency of antifouling paints, such as chlorothalonil, dichlofluanid, DCOIT (4,5-dichloro-2-octyl-1,2-thiazol-3(2H)-one), Diuron$^{\text{TM}}$, Irgarol$^{\text{TM}}$1051, Sea-nine$^{\text{TM}}$211, zinc pyrithione, zineb$^{\text{TM}}$, TCMTB ((Benzothiazol-2-ylthio)methyl thiocyanate), and TCMS pyridine (2,3,5,6-tetrachloro-4-(metylsulphonyl)pyridine) (Alyuruk and Cavas 2013; Guardiola et al. 2012). Some of these biocides, such as chlorothalonil, dichlofluanid and zined, are also used in agriculture as pesticides or fungicides. There is evidence of effects of biocides on non-target species and also of the bioaccumulation of some of the biocides. For example, DCOIT has been shown to accumulate in fish and Irgarol 1051 in macrophytes and the green alga. Moreover, biocides may contribute to the increase in in the occurrence of antibiotic resistant bacteria.(Guardiola et al. 2012)

Biocidal Products Directive (BPD) controls biocidal products substances that are sold in the EU market. Some National level regulations also limit the use of certain antifouling paints. For example, use of Irgarol is prohibited in the United Kingdom, Denmark and Sweden, and use of Diuron in the Netherlands and United Kingdom. (Saleh et al. 2016)

3.3 Noise

Sound is vibration that propagates through a transmission medium and in the case of recreational boating, this medium can be air, water or the structures of the craft. The engine, air inlet and the interaction of the water and the hull are major sources of the noise disturbance to the air. If the exhaust outlet is not below water surface, it will create an additional source for airborne sound. The engine, vibration of the boat structures, the propeller, flow around the hull, and exhaust gas if the exhaust outlet is located underwater are major sources are the underwater sound. (TNO 2004) Watercraft noise may disturb people in the surrounding areas, but can also have an impact on the local ecosystem. The hearing range of different animal species vary and therefore, the noise emission from recreational watercrafts has different impact on different species. Moreover, how much species depend on sound on their natural activities is unambiguous. (Slabbekoorn et al. 2010) A study on flushing of birds due to passing boats or PWCs by Rodgers and Schwikert (2002) revealed that the distance between the boat and the bird causing the bird to escape varied depending on the species. Measured sound levels at 10 metres from the craft were 87 dBA for an outboard motorboat and 83 dBA for a PWC.

Measuring and estimating the level of underwater noise is difficult as the operation and the surrounding environment affect the generated noise level. The installed power has some effect on the generated noise level, but the operation method of the boat, such as speeding, can have a larger impact. Characteristics of the operation environment, such as geometry and geology of the bottom, water velocity, temperature and the depth, have an important role in the range and environmental impact of the noise emission. In water, sound travels faster than in the air and attenuates less easily. (Slabbekoorn et al. 2010) There have been attempts to estimate the impact of underwater noise on an aquatic ecosystem. Rako et al. (2013) discovered a correlation between presence of recreational watercraft and sea ambient noise levels. Monitoring of bottlenose dolphins in the boating area revealed that the underwater noise may have long-term effects on the dolphin population.

Noise generated by personal watercrafts has been described to be more annoying than noise emission from other recreational watercraft types. While the sound generated by PWC is not louder than sound from other watercraft types, it is more disruptive mainly due to the operation behaviour, such as high speeding and continuously circulation in the same area. Moreover, the ability of PWC to travel in shallow water near the shoreline increases the potential to disturb local residents and for example, bird populations. However, underwater noise levels generated by PWC are lower than noise levels from operation of small powerboats. (Erbe 2013; Rodgers and Schwikert 2002)

3.4 Other environmental pressures

Recreational boating can have a direct physical impact on the environment and animal species. Movement of a boat on water surface creates a series of waves whose magnitude and form depends on hull characteristics, the velocity of the vessel and water currents. The produced wake can contribute to the erosion of the environment, sediment transportation and may even directly destroy nests of animal species living in the water or at the shore. Moreover, species living or moving in the water can be killed or injured in a collision with a boat, especially if the animal is in physical contact with the propeller. (McConchie and Toleman 2003; Burgin and Hardiman 2011)

Marine debris has received a lot attention recently and it has to be noted that recreational boating may be one source of solid waste in water systems. Waste generated during boating is most likely similar to the household waste, but may also contain batteries, electronics and waste engine oil, which would require special treatment. More than 150 different IMO member countries have signed the MARPOL Annex V, which controls the garbage discharged to the sea. It states that discharging any other than organic waste to the sea is prohibited. Grounded or comminuted food waste can be discharged when the distance to the nearest land area is at least 3 nautical miles, or at least 12 nautical miles in 'special zones', such as the Baltic Sea or the Mediterranean Sea. Without grounding or comminuting, food waste can be discharged within a minimum distance of 12 nautical miles from land areas outside special areas and in special areas not at all.

There are several water sports and other activities, which are related to boating, and might create additional pressures on the environment. Recreational fishing is an activity strongly related to boating and there is evidence that the contribution of recreational fishing to the declines in fish population is larger than has been estimated (Cooke and Cowx 2004; Lewin et al. 2006). Recreational fishing concentrates on freshwater systems and coastline areas of oceans, which are often inaccessible for commercial fisheries. Lack of data has been a major challenge for estimating environmental impact of recreational fishing (Cooke and Cowx 2004) and better understanding of the distribution of boating activities could also support these estimations.

4 Material and methods

4.1 Dataset

The global AIS dataset from year 2017 comprised the main material of this study. The dataset contains AIS messages sent from 448996 different MMSI numbers during 2017. Each message contains MMSI number of the vessel, timestamp in UTC standard time, coordinates of the vessel location and the current speed and course of the vessel. Following table 1 shows an example of the dataset, each line corresponding to one AIS message.

Table 1: Example of the structure of the AIS data used in this study.

Time (UTC)	longitude	latitude	speed	course
2017-08-19T10:04:48	153.256240	-24.182121	14.7	317
2017-08-19T10:08:12	153.245730	-24.171957	14.7	316
2017-08-19T10:09:54	153.240700	-24.166868	14.7	318
2017-08-19T10:13:25	153.230300	-24.156084	14.8	318

The frequency of received messages depends on the operation mode of the ship, type of the AIS transmitter and the coverage of the AIS network at the location of the ship. Most powerful transmitters can send messages as frequently as every 3 seconds and therefore the number of AIS messages is high. Total number of AIS messages in the dataset used in this study is nearly 4 billion. Figure 7 shows the fraction of AIS messages per day in the AIS dataset used in this study. There is some variation, but overall the activity remains at the same level throughout the year. There are individual days with significantly lower rate of AIS messages in comparison to the average situation. These drops are most likely caused by blackouts in the network, which can be caused by maintenance works or technical failures.

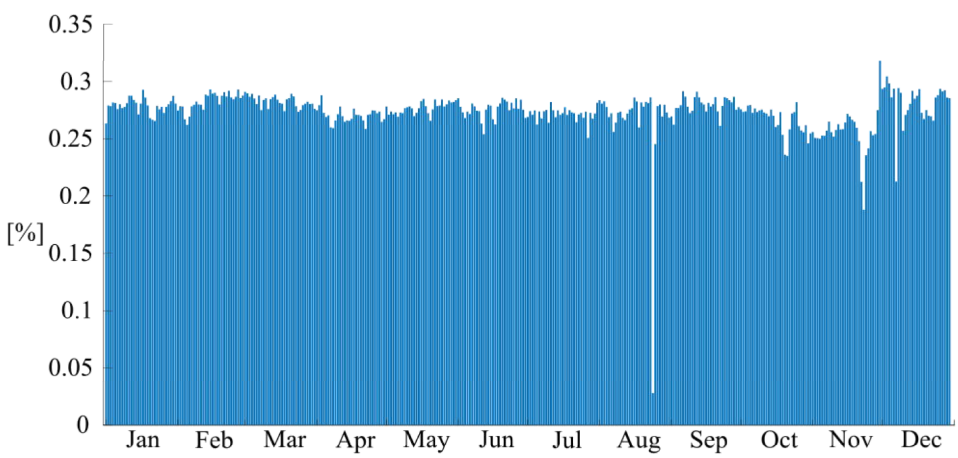


Figure 7: Distribution of AIS messages over the year 2017.

Figure 8 shows the share of AIS messages during different times of the day and days of the week. Overall, the activity remains stable although some weak trends can be observed. Distribution over the week shows a decrease in the number of AIS messages during Friday and Saturday. Also, increase in the number of AIS messages can be observed during the morning hours.

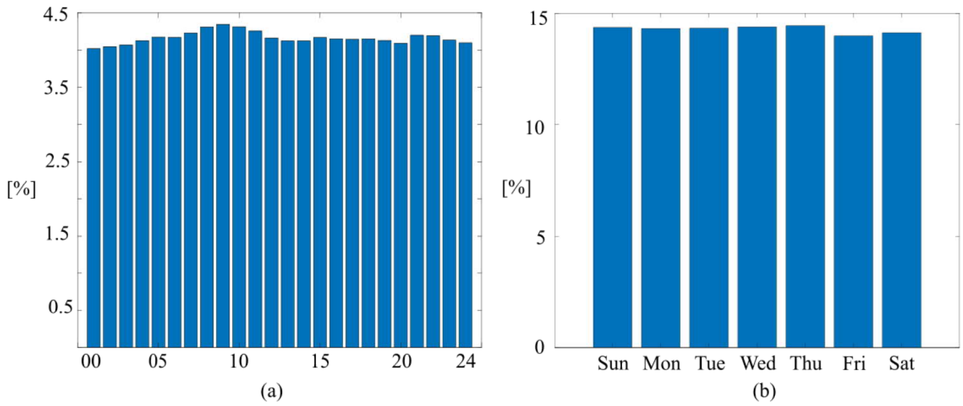


Figure 8: Distribution of received AIS messages per hour of the day (a) and day of the week (b).

Spatial distribution of messages in the AIS dataset for the year 2017 is shown in the figure 9. Coastlines and major seaways are well represented, as well as the most important fishing areas. Even though AIS is mainly used by seagoing vessels, some level of activity can also be observed in the largest rivers and inland waters.

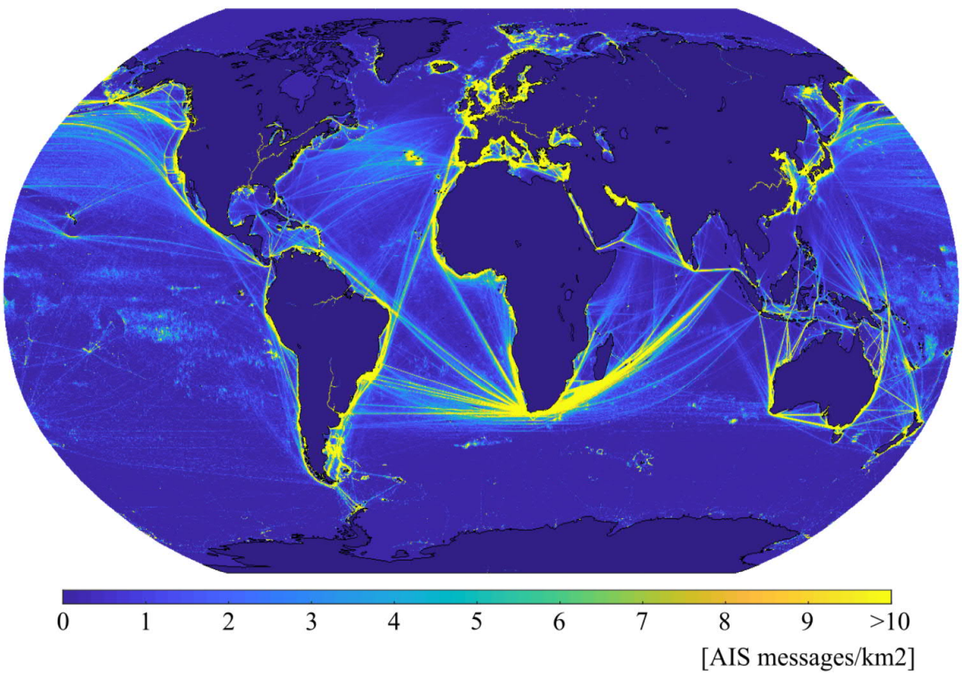


Figure 9: Geographical distribution of AIS messages received during year 2017.

Figure 10 shows the share of MMSI codes sending AIS messages under different flag states in the AIS dataset. These fractions are based on MID codes, the first three digits of the MMSI number, which indicate the flag state of the vessel. The highest numbers of different MMSI codes sending AIS messages in the dataset are under the flag of China, the Netherlands and USA. These fractions should not be confused with actual sizes of the fleet of these flag states, as many other aspects, such as AIS network coverage and AIS related legislation, affect the number of vessels visible in the AIS dataset.

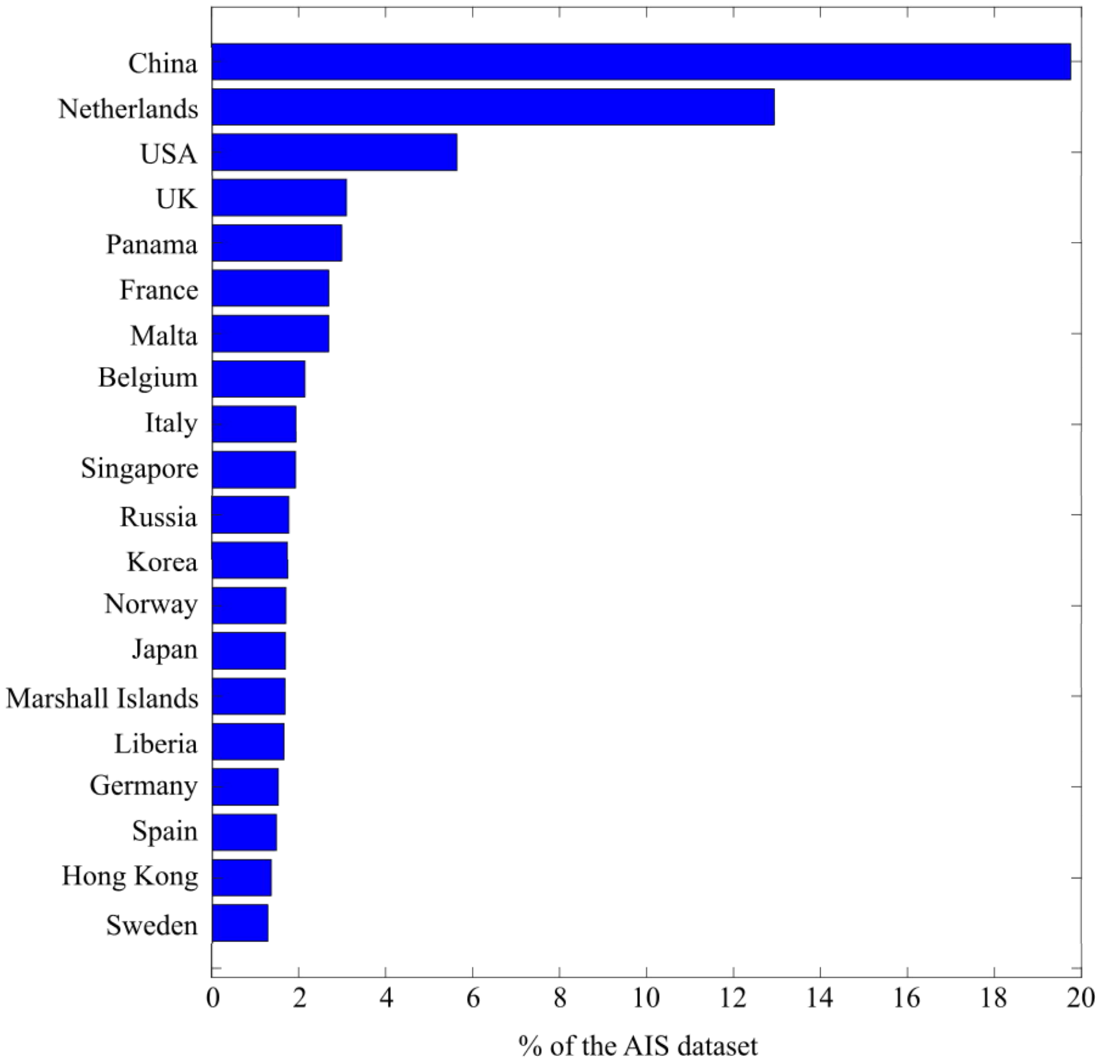


Figure 10: Share of vessels sailing under the largest flag states according to the AIS dataset.

4.2 Procedure for creating activity profiles

MATLAB software was used to construct an algorithm that reads AIS messages in the AIS dataset and identifies recreational watercraft from other possible vessel types. This algorithm was used to estimate spatial and temporal activity profiles for the identified recreational watercraft. Recreational watercraft were identified using criteria based on current knowledge about use of boats. Criteria used in this study are discussed in more detail in chapter 4.2.1. To estimate the distance and path recreational watercraft have travelled, interpolation is needed between reported locations. The method used for the interpolation is discussed in chapter 4.2.2. Estimation of profiles of the activity is described in chapter 4.2.3. Literature review conducted to estimate the level of emissions from recreational watercraft is described in chapter 4.2.4

4.2.1 Identification of recreational watercraft

Due to a large amount of data, the identification of recreational watercraft needed to be done efficiently so that unnecessary calculations were avoided. This means that if the vessel was identified as of any other type than recreational, it was neglected immediately. Also criteria, which can be used for the identification without interpolation between known locations were implemented first to decrease the calculation time. Requirements, which all recreational watercraft were assumed to meet were:

1. The annual total travelled distance is 1000 nautical miles (1852 km) or
2. The vessel has been active during 50 days or less during the year
3. The vessel does not operate in areas of sea ice
4. MMSI code starts with a MID code (the first digit is in the range of 2 – 7) according to the AIS – data
5. Vessel is not recognised as a fishing vessel by the Global Fishing Watch

The dataset contained MMSI codes, which have sent only few AIS messages during the year 2017. With insufficient number of location reports, it is not feasible to estimate the activity of the vessel and furthermore, to define the vessel type. Moreover, it is possible that these MMSI codes with only few reported locations are actually erroneous and therefore should be neglected. Hence, only vessels with enough reported locations were included in this study using a limit of minimum 100 AIS messages sent. MMSI codes with less than 100 AIS messages for the year 2017 are automatically neglected. Similar limit has been used by Global Fishing Watch for identification of fishing vessels (Kroodsma 2016).

One of the criteria chosen for the identification was the total distance the vessel travelled during the year. Boats used only for recreational purposes are assumed not to operate at an intensity comparable to commercial vessels. The maximum annual distance travelled by a recreational boat is assumed to be 1000 nautical miles (corresponds to approximately 1852 km). Additionally, recreational watercraft are not used as regularly as commercial vessels and a limit of maximum 50 days of annual usage is set for recreational watercraft. The largest seagoing watercraft, especially large sailboats, might be filtered out from the analysis along with these requirements. However, increasing the distance or usage rate limits would most likely lead to increase in the number of other vessel types falsely identified as recreational.

Recreational boats are assumed not to travel in areas of sea ice coverage and this is used as one criteria for filtering commercial vessels in the dataset. Sea ice coverage is based on the global Sea ice concentration and snow extent data for the year 2017 published by NASA Earth Observations. Monthly data is not available and 15th day of each month is used to represent the sea ice situation during the month. Resolution of the data is 0.5 degrees and it has been collected by National Snow and Ice Data Center (NSIDC). (NEO 2017) If a vessel is operating in an area of sea ice, it is not identified as a recreational boat and is therefore neglected in this study.

Individual ships use MMSI codes starting with a number from 2 to 7 and therefore AIS messages sent with MMSI code starting with a number outside of this range are neglected. There are several databases available that provide technical information about vessels, which could be used to further identify different vessel types from the dataset. However, MMSI code of a vessel can change and the previous code might be given to a new vessel in a case when a vessel is removed from use, or is changing owner or the flag state. Therefore, it is not certain that MMSI codes in recently updated databases correspond to MMSI codes in the dataset from year 2017. In this study, it is assumed that each unique MMSI code corresponds to one vessel and that these codes are not changing during the year 2017. Global Fishing Watch is an organisation tracking the commercial fishing fleet and provides a list of vessels recognised as fishing vessels for years 2012 – 2017 (GFW 2018). This list of MMSI codes of identified fishing vessels in year 2017 is used to filter out commercial fishing vessels from the AIS dataset.

4.2.2 Interpolation between known vessel locations

The frequency of AIS messages sent by a vessel varies and sometimes the time gap between consecutive messages can be long. To estimate the distance a vessel has travelled, and the spatial distribution of the activity, interpolation is often needed. The vessel is assumed to travel using the shortest possible path between two known locations and land areas, or other possible obstacles, are not taken into account. Johansson et al. (2017) describes a method for taking possible shipping routes into account, which could also be used in the case of recreational watercraft in the future. The blackout between known locations can be large, and therefore, it is not always reasonable to interpolate the path between them. Moreover, AIS messages occasionally contain erroneous coordinates which should be neglected when estimating the travelled route. Two requirements are given to avoid unrealistic estimations of the path the vessel has travelled:

1. The time difference between known locations must be 24 hours or less
2. The calculated speed of the vessel must not exceed 200 km/h

The speed is estimated by calculating the distance and the time difference between two successive known locations. The maximum speed limit of 200 km/h is high and only fastest boats could travel with a higher velocity. Also, the method used will most likely underestimate the real velocity of the vessel as it is assumed to travel the shortest possible path. The distance between two successive coordinate points is calculated using the Haversine formula for the great-circle distance:

$$\alpha = \sin^2(\frac{\varphi_2 - \varphi_1}{2}) + \cos(\varphi_1)\cos(\varphi_2)\sin^2(\frac{\lambda_2 - \lambda_1}{2}), \tag{1}$$

$$d = 2atan2(\sqrt{a}, \sqrt{1-a}), \tag{2}$$

where d is the distance between two coordinate points (φ_1, λ_1) and (φ_2, λ_2) in radians (Sinnott 1984). Distance calculated in radians is transformed into kilometres by multiplying it by the earth radius R:

$$D = d * R, \tag{3}$$

Using Haversine formula means that the earth is assumed to be a great-circle when actually it is elliptic. The radius varies from 6357 km to 6378 km and an average value of 6371 km is used in this study. However, the aim is not to obtain the exact distances vessels have travelled and therefore, the error caused by the ellipticity is not significant in this case. The track between known locations is interpolated by generating new points with a spacing of 1 km between them. Coordinates for intermediate points are defined by using geodesic normal vectors. Coordinates of two successive location points are converted from latitude and longitude to the geodesic normal vector by using the equation:

$$\bar{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \begin{bmatrix} \cos(\varphi)cos(\lambda) \\ \cos(\varphi)\sin(\lambda) \\ \sin(\varphi) \end{bmatrix}, \tag{4}$$

The geodesic normal vector of an intermediate point at a fraction f along the track between points 1 and 2 is defined as:

$$\bar{n}_i = \bar{n}_1 \frac{\sin((1-f)d)}{\sin(d)} + \bar{n}_2 \frac{\sin(fd)}{\sin(d)}, \tag{5}$$

where f is the fraction of the travelled route between two points so that at the starting point, $f = 0$, and at ending point $f = 1$. The geodesic normal vector of the intermediate point can be converted back to coordinates in latitude and longitude by using the equations:

$$\varphi_i = atan2(n_{zi}, \sqrt{n_{xi}^2 + n_{yi}^2}), \tag{6}$$

$$\lambda_i = atan2(n_{yi}, n_{xi}), \tag{7}$$

where φ_i and λ_i are coordinates of the intermediate point at the fraction f along the track. (Tseng and Lee 2007) Fraction f is defined based on the distance between the two locations so that intermediate points are generated at a constant spacing of 1 km. All the grid cells the created line passes through are assumed to have been visited by the boat.

4.2.3 Defining spatial and temporal activity profiles

The number of AIS messages sent by identified recreational watercraft could be used as an indicator of boating activity. However, a vessel will transmit AIS messages also when it is anchored and therefore only counting AIS messages might lead to misleading results. Moreover, possible erroneous messages would also disturb the generated activity profiles. To reduce the effect of the possible erroneous messages in the AIS dataset, the total distance travelled was used as an indicator for the boating activity level instead of the number of received AIS messages. The method for distance estimation is described in chapter 2.3.2. For the geographical distribution, the number of boat visits per cell was used to indicate the activity instead of the number of received AIS messages.

Geographical activity was estimated using a mesh with a grid cell size of 0.05 degree both in latitudinal and longitudinal directions. The boating activity was estimated by counting the number of boat visits per grid cell taking the interpolated track between known locations into account. Only one visit is counted even if the boat remains for a longer time at the same location. However, if the boat moves and later returns again to the location it has already visited, it will contribute to a new boat visit at that location. As the mesh is defined based on latitude and longitude degrees, the grid cell size is not constant and therefore results were normalised with the cell area. Land area of a grid cell was calculated based on the location of the centre point of the cell.

Temporal distribution was generated based on the total distance recreational watercraft have travelled. Timestamps in the AIS dataset are given in UTC standard time, which is not the optimal format for estimating boater behaviour profiles. Local time zones are defined as offset from UTC and each country can choose the time zone it officially follows. In most countries, the official time zones are not in line with the solar time defined by the geographical location of the country. In this study, the time zone of the vessel was defined only according to the longitudinal coordinate of the vessel location following the solar time. This means that in some areas, the defined local time is not the same as the official local time of the country.

Existing knowledge was used to estimate the performance of the algorithm and the accuracy of the generated activity profiles. In addition to results from boating surveys, locations of recreational boating marinas were also used to estimate the geographical distribution of the boating activity. Open street map (OSM) is a project based on voluntary geographic information, meaning that individual users may freely add data to the map and also use the data added by other users. The database contains information about leisure marina locations, which was used to estimate the distribution of boat marinas, and to evaluate the accuracy of the generated geographical distribution of recreational watercraft.

4.3 Literature review

A systematic literature review was conducted to answer research questions about the level of emissions generated during the operation of recreation watercraft. The aim was to find articles and reports that provide quantitative estimates of the emission rates of recreational marine engines, antifouling paints and wastewater. The search was conducted manually using the database of Google Scholar. As the number of studies about boating emissions is limited, also less reliable databases, such as Google had to be used to find all existing information. For the same reason, the review was not limited to peer-review articles, but also other documents, such as conference papers, industrial reports and news were considered. The main criteria for choosing the studies included in the review was that they propose emission rates that could be used for developing emission inventories and models. Especially measurements of emission rates during the operation of watercraft were searched for.

Combination of strings that was used in the search is listed in table 2 with the number of results in the Google scholar database. The only limitation set for the search was that patents were not included. Both “boat” and “recreational watercraft” were used as the first part of the string. Additionally, reference lists of the papers found during the review were utilised.

Table 2: Strings used for the search and the number of hits in the Google Scholar. Top row shows the first part of the string and the first column shows the second part of the string.

	boat*	recreational watercraft*
*emissions	55000	2160
*nitrogen oxide emissions	24100	6910
*particulate matter emissions	20200	11800
*carbon monoxide emissions	14400	17800
*volatile organic compound emissions	23700	4680
*carbon dioxide emissions	31500	13000
*hydrocarbon emissions	24500	770
*wastewater	32100	1400
*antifouling	3360	313
*noise	36300	1140

5 Results

5.1 Boating at global level

Figure 11 shows the distribution of recreational marinas according to Open Street Map data. Dataset contains locations for a total of 13201 recreational marinas in different parts of the world. The highest number of recreational marinas is found in Europe, followed by the North America and Asia.

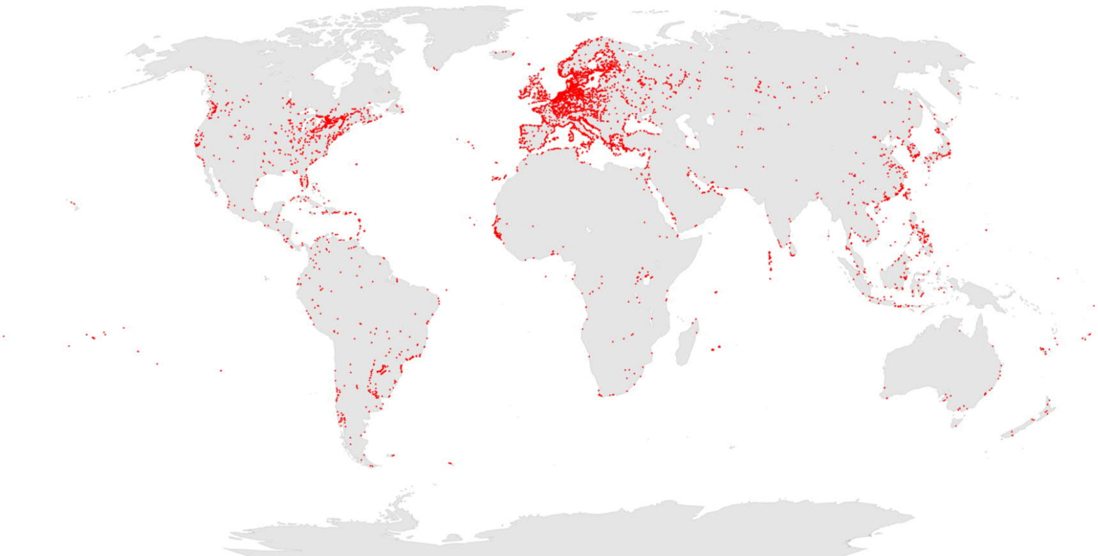


Figure 11: Locations of recreational marinas according to the dataset by Open Street Map (OpenStreetMap contributors 2018).

The algorithm identified a total of 19047 vessels as recreational watercraft from the AIS dataset for the year 2017. Geographical distribution of these boats is shown in figure 12. The identified recreational watercraft correspond to approximately 4.2 % of the total number of the vessels in the dataset. The highest boating activity levels can be found in Europe, East Asia and North America. The activity is strongly concentrated in coastal areas and in areas of high population density. Some activity can also be seen in largest rivers and inland waters. Globally, the average distance travelled by a boat during the year was 214 km. There is some variation between different areas; the average distance was lowest in the Netherlands with 87 km/boat and highest in Australia with 244 km/boat.

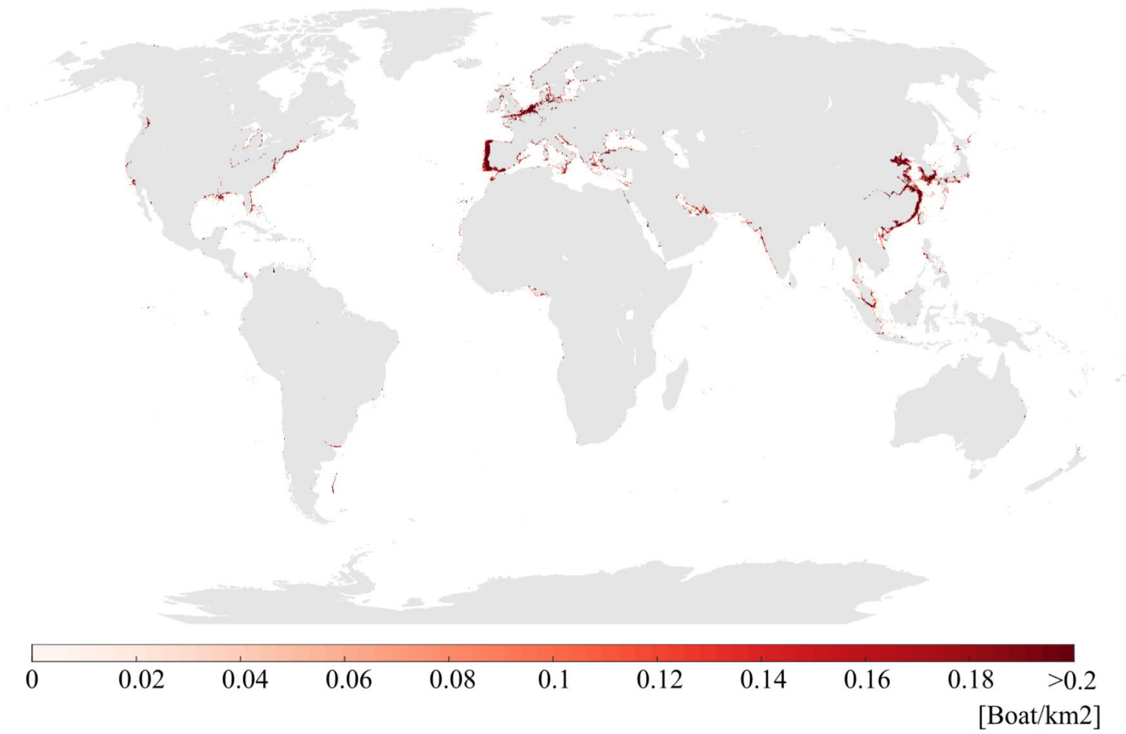


Figure 12: Total intensity of boating activity during year 2017.

Figure 13 shows the temporal distribution of the activity of identified recreational watercraft globally during the year 2017. There are two visible trends in the distribution; the activity increases in the summer and winter seasons and is at its lowest from February to April and October to November. Drops in the activity for individual days are most likely caused by blackouts in the dataset and therefore, they do not indicate low boating activity. Highest activity peaks are observed in the end of December.

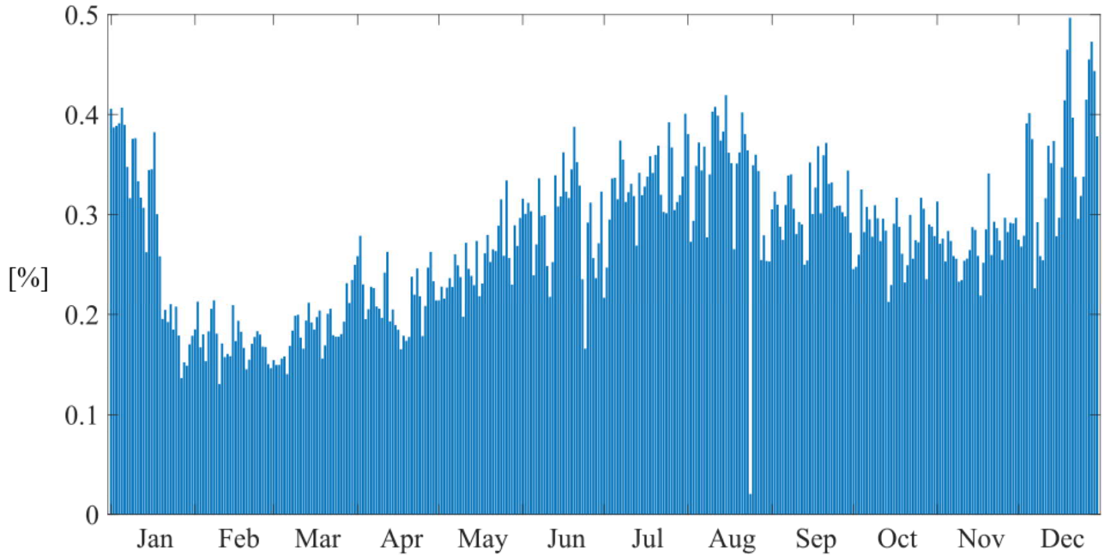


Figure 13: Distribution of the distance travelled by recreational watercraft globally in 2017.

Figure 14 shows the distribution of the global boating activity during different hours of the day and days of the week. The activity increases during the day time and the highest activity peak is between 10 am and 11 am. During the night, the activity level decreases to less than one third of the observed daily maximum. There is no large variation between activities of different days of the week, but a slight increase can be observed from Tuesday to Thursday.

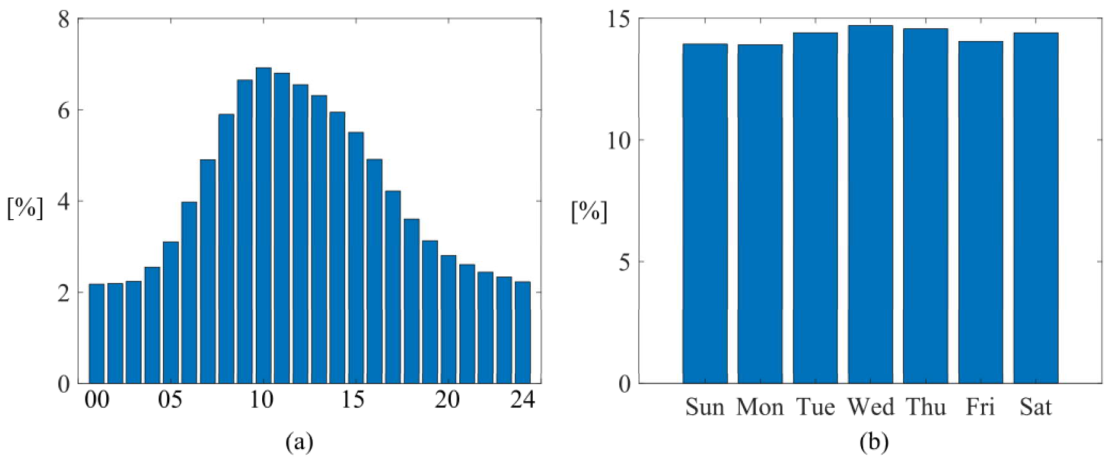


Figure 14: Hourly (a) and daily (b) distributions of the recreational watercraft activity.

Figure 15 shows the share of identified recreational watercraft under the largest flag states. Highest number of boats were identified to be sailing under the flag of China, followed by the Netherlands and the USA. The proportion of vessels identified as recreational watercraft is 7.2 % in China, 2.4 % in the Netherlands and 5.9 % in the USA. The largest proportion was in Lesotho in Southern Africa with more than 30 % of vessels identified as recreational.

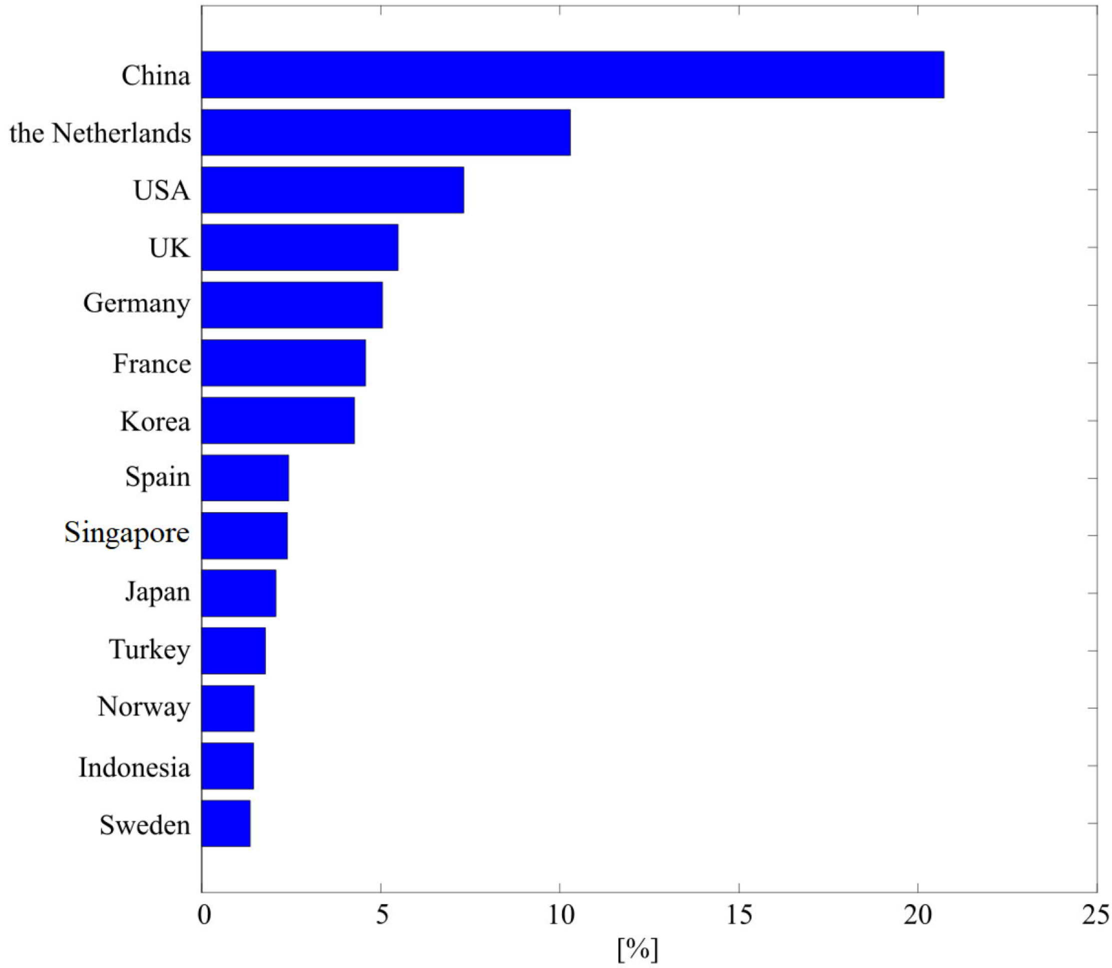


Figure 15: Share of recreational watercraft under the largest flag states.

5.2 Boating in Europe

With a total of 8506 reported recreational marina locations, Europe is the most popular region for recreational boating according to the OSM dataset. Figure 16 shows how these marinas are distributed in Europe. The highest densities of marinas can be found in the northwest Europe, along with the largest rivers in the central Europe and at the coastline of the Mediterranean Sea.

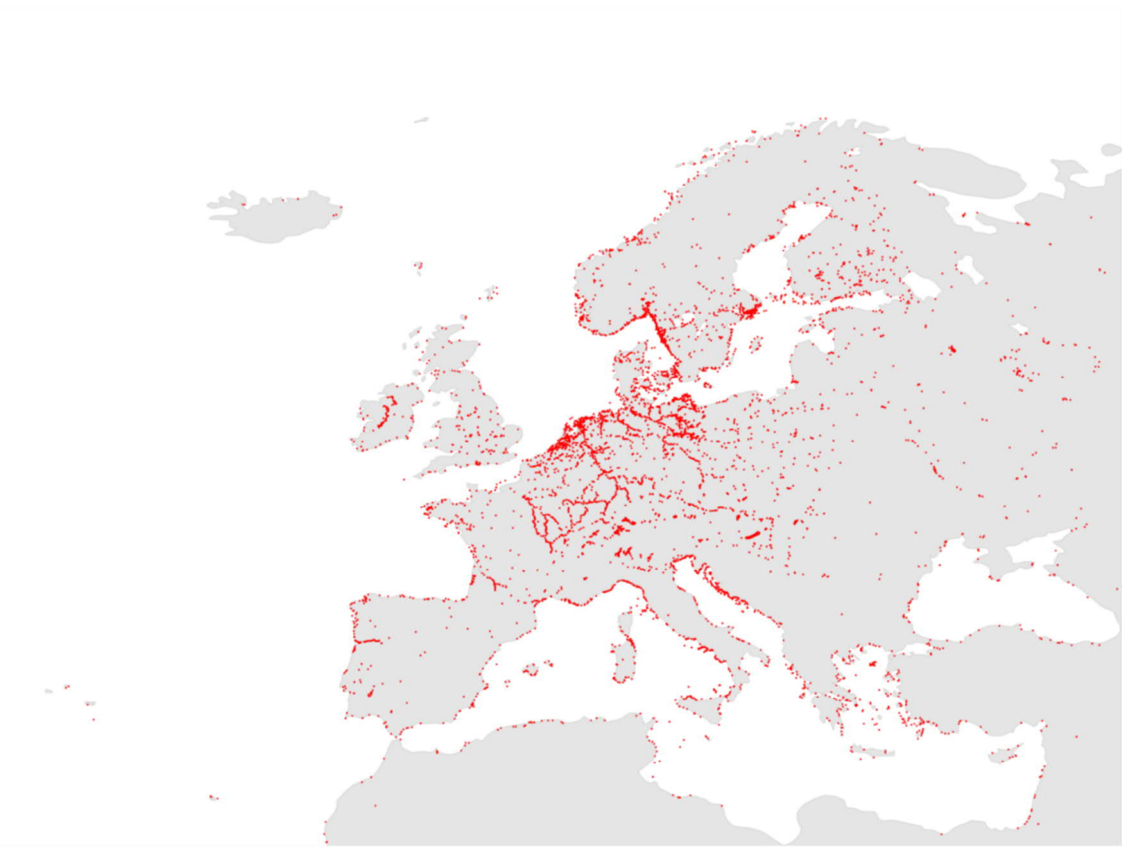


Figure 16: Locations of recreational marinas according to the dataset by Open Street Map (OpenStreetMap contributors 2018).

A total of 7560 vessels were identified as recreational within Europe. Figure 17 shows the geographical distribution of the boating activity during different seasons in Europe according to the AIS dataset. The largest hot spots are in the coastline of Portugal, Spain and the Netherlands. Boating activity is concentrated in coastal sea areas, inland waters and in archipelagoes. At the Baltic Sea, the boating activity has strong seasonal variation and is at its highest rate during summer and at the lowest during winter season. At the North Sea, the coastline of Portugal and the Mediterranean Sea, some level of activity remains throughout the year. Still, a trend of decreasing activity during the winter and increasing during the summer season can be observed. The coastline of Norway at the Norwegian Sea shows different trend than other regions as the number of boat visits is slightly increasing during winter.

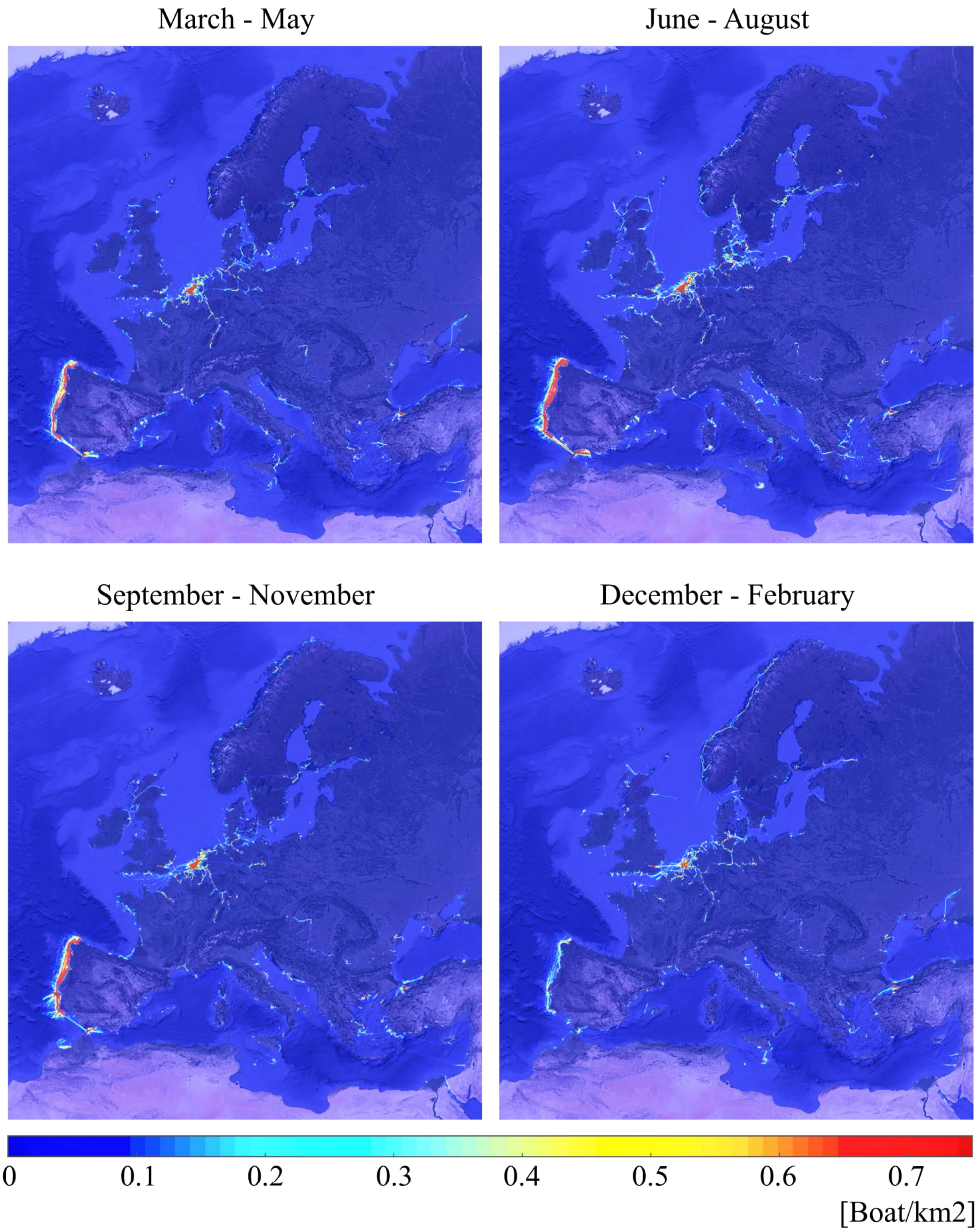


Figure 17: Number of recreational watercraft visits in Europe during different seasons of 2017. Plotted on Google Earth.

Temporal distribution of the boating activity in Europe is shown in figure 18. Daily distribution over the year 2017 shows a clear increase in the boating activity during the summer season. Activity begins to increase in early April and peaks during June, July and August. The highest activity peak takes place on the 22nd of June, right before the Saint John's Eve and the midsummer celebration. There is an increasing trend in the activity rate until mid-august and after that, the activity rates decrease. Boating activity is at the lowest level during February.

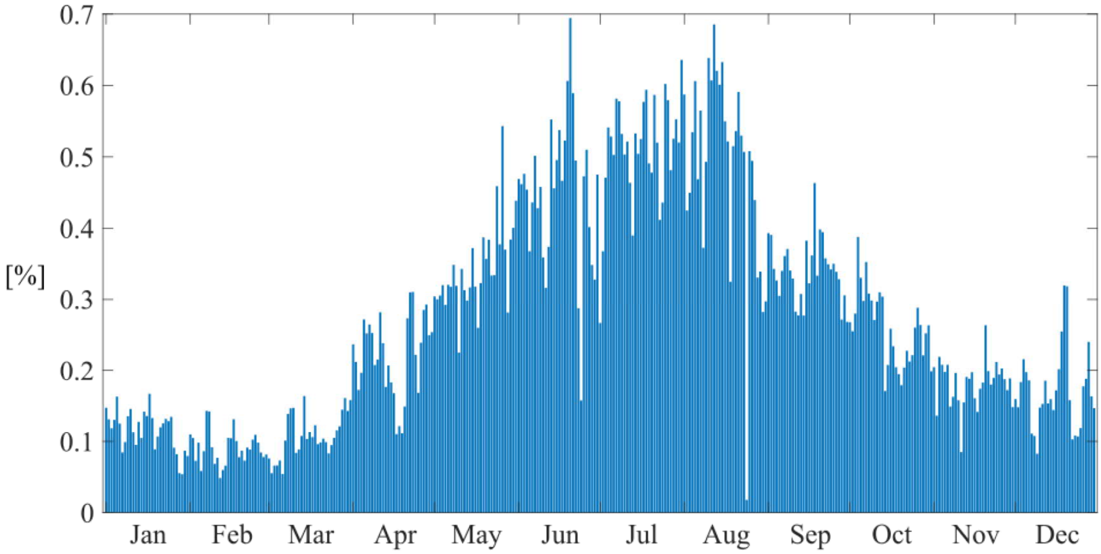


Figure 18: Distribution of the distance travelled by recreational watercraft in Europe in 2017.

Figure 19 shows the activity of identified recreational watercraft in Europe for different hours of the day and days of the week. The hourly activity increases starting from 4 am, peaking between 10 am and 11 am and then decreases towards the evening. During the night, the activity remains at a level lower than a quarter of the activity level during the day time. The variation between different days of the week is minor, but a slight increase in the activity can be observed on Tuesday, Wednesday Thursday and Saturday.

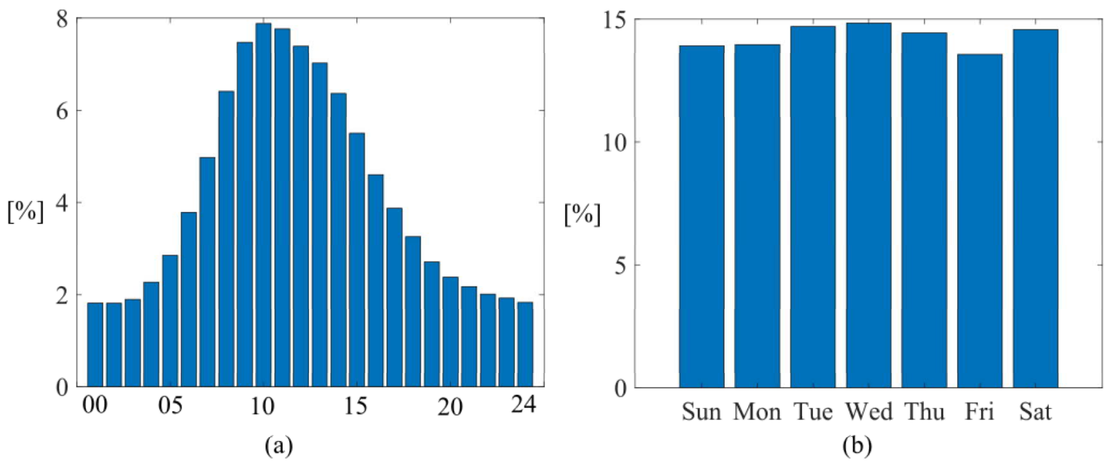


Figure 19: Hourly (a) and daily (b) distributions of the recreational watercraft activity in Europe.

5.3 Boating in North America

The OSM dataset contains locations for a total of 1453 leisure marinas in North America. Figure 20 shows geographical distribution of these marinas. The highest concentration of marinas can be found in the western border of the USA and Canada, around Lake Ontario, Lake Erie and Lake Huron, and St. Lawrence River. Also, the surroundings of New York, Washington and Vancouver, California and Florida include a high number of marinas.

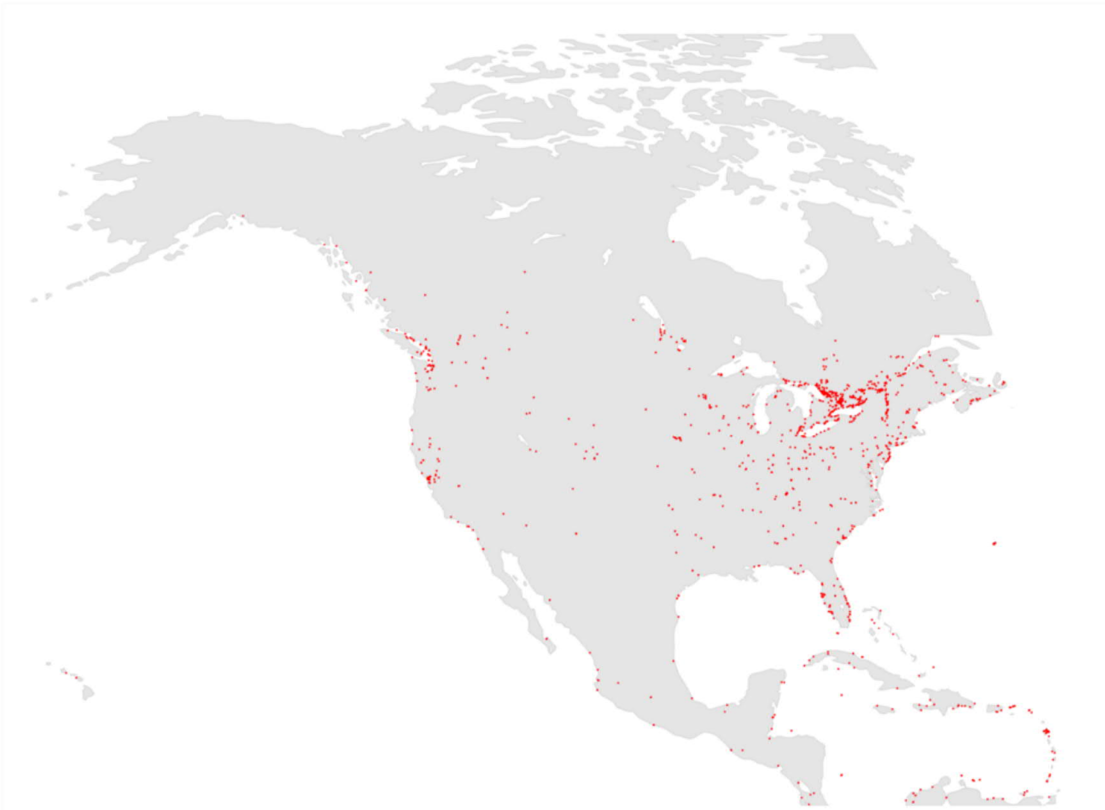


Figure 20: Locations of recreational marinas according to the dataset by Open Street Map (OpenStreetMap contributors 2018).

A total of 1282 recreational watercraft were identified in the area of North America. Figure 21 shows the spatial distribution of boating activity for different seasons in 2017. Highest activity levels take place in the surroundings of New York, Lake Michigan and Lake Huron, Washington, California, New Orleans and Florida. In the northern parts of the country, boating activity increases during summer season and decreases during winter. In Florida, the boating activity remains nearly constant all seasons and in the Mississippi delta, the activity increases during the winter season. Areas with the highest numbers of boat detections are mainly within 20 – 30 km from the coastline, but in areas with archipelago and in gulfs, the range of the boating activity is wider.

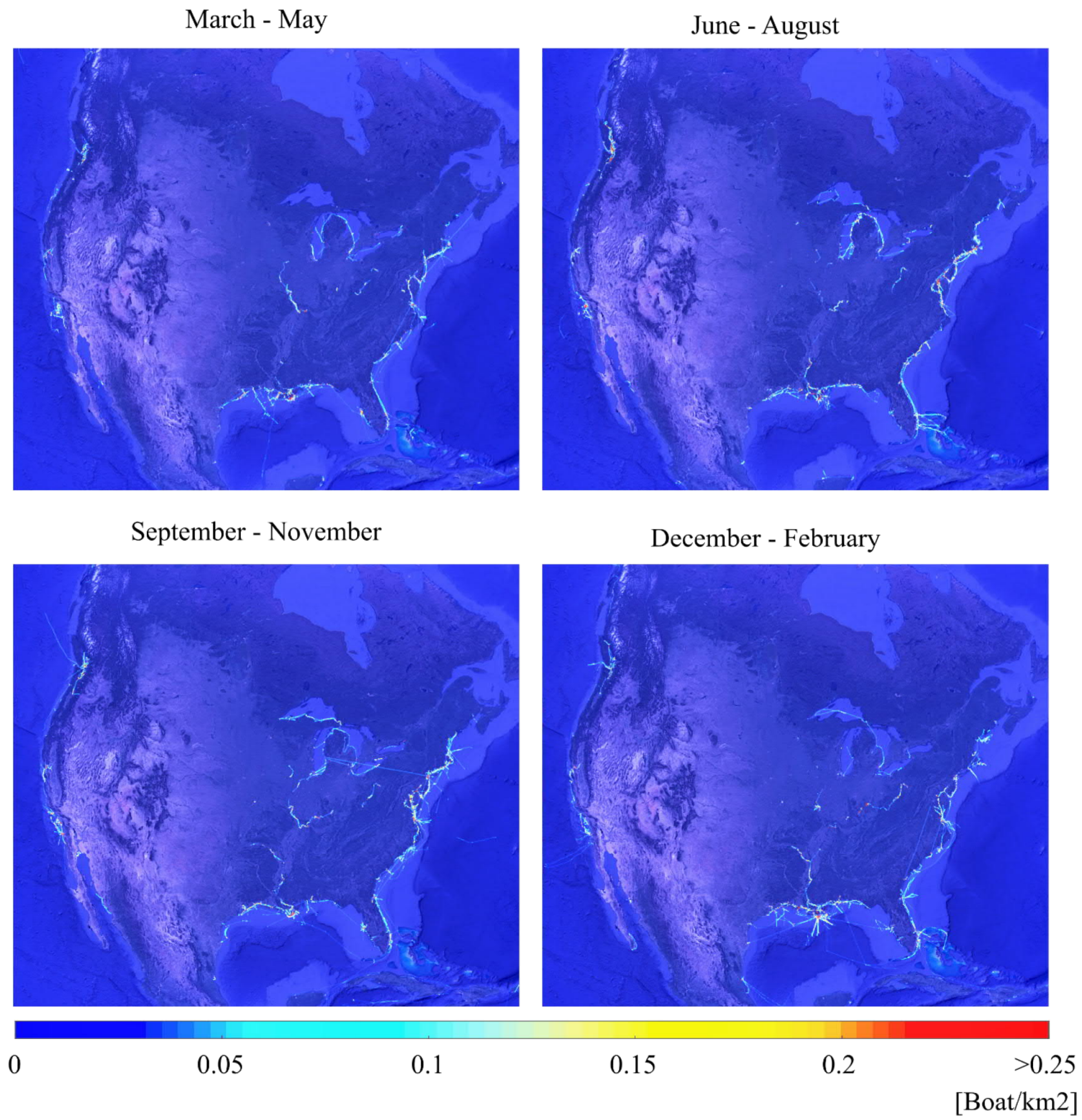


Figure 21: Number of recreational watercraft visits in North America during different seasons of 2017. Plotted on Google Earth.

Temporal variation of the activity of identified recreational watercraft is shown in figure 22. The boating activity increases both during the summer season and winter season. The activity rates are at their lowest in February and March, and the highest activity peaks are in December and early January. A large variation between the activity levels of different days can be observed.

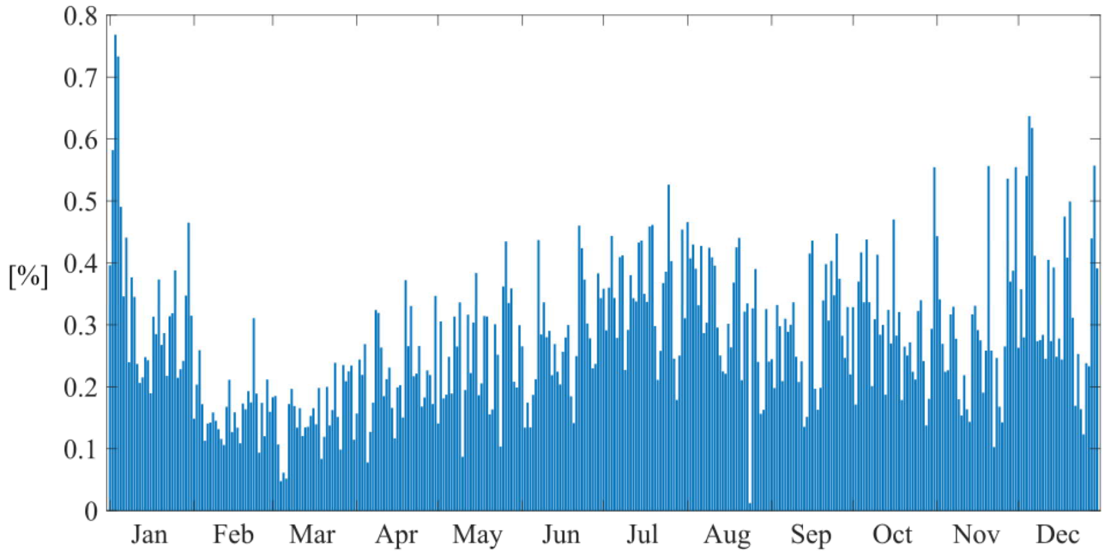


Figure 22: Distribution of the distance travelled by recreational watercraft in North America in 2017.

Distribution of the boating activity over the hours of the day and days of the week are presented in figure 23. Increase in the boating activity level can be observed from 4 am to 9 pm with the highest activity taking place between 10 am and 11 am. During the night, the activity level remains below 2 % of the total activity per hour. Weekly distribution shows that the activity increases slightly on Tuesday, Wednesday and Thursday.

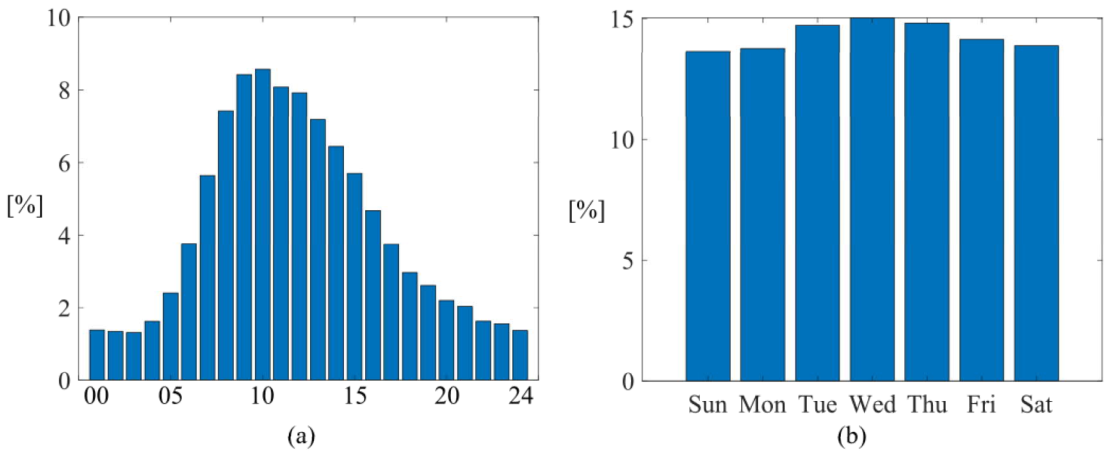


Figure 23: Hourly (a) and daily (b) distributions of the recreational watercraft activity in North America.

5.4 Boating in East Asia

Locations for 557 recreational marinas have been reported in the OSM in the area of East Asia. Figure 24 shows these locations. Recreational marinas are concentrated in South Korea, Japan and Southeast China. Most of the marinas are located along the coastline but some are also following the largest rivers, such as Yangtze River in China.

Figure 24: Locations of recreational marinas according to the dataset by Open Street Map (OpenStreetMap contributors 2018).

A total of 5255 watercraft were identified as recreational in the East Asia. Geographical distribution of these watercraft is shown in the figure 25. The watercraft are concentrated in the Yellow Sea, Yangtze River, surroundings of Hong Kong and Macau, South Korea and the southern parts of Japan. In China, the boating activity seems to be at the lowest level during the summer season and at the highest from September to February. In South Korea, the boating activity decreases during the winter, but near the coastline the activity rate remains high throughout the year. As in China, in Japan the boating activity seems to be at the highest level between September and February.

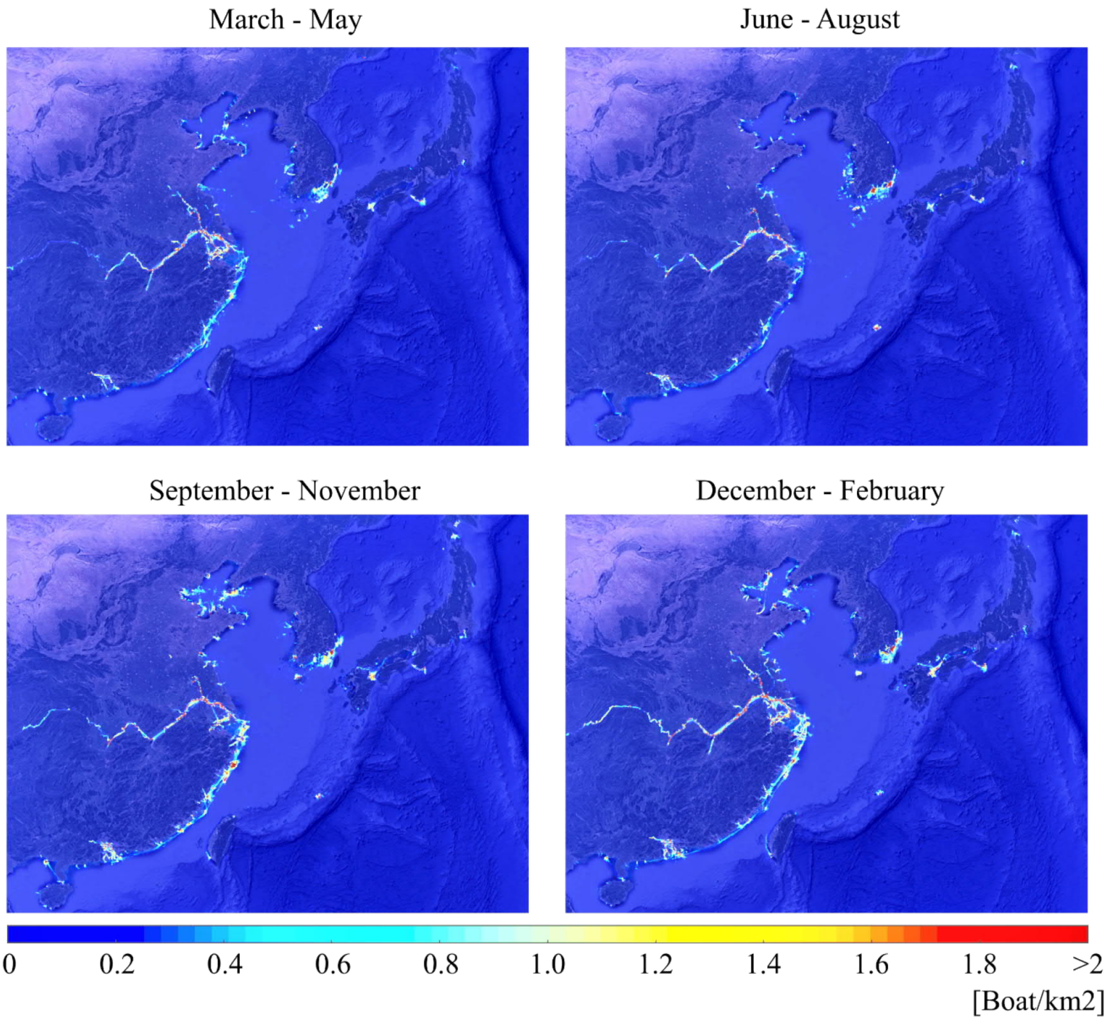


Figure 25: Number of recreational watercraft visits in East Asia during different seasons of 2017. Plotted on Google Earth.

Annual distribution of the activity of identified recreational watercraft is shown in figure 26. Temporal profile of recreational boating activity in East Asia shows different trends in comparison to other regions in the northern hemisphere. The level of boating activity is at the highest during winter season and decreases during summer. Also, a decrease in the activity can be seen during the Chinese New Year, which took place on the 28th of January in 2017.

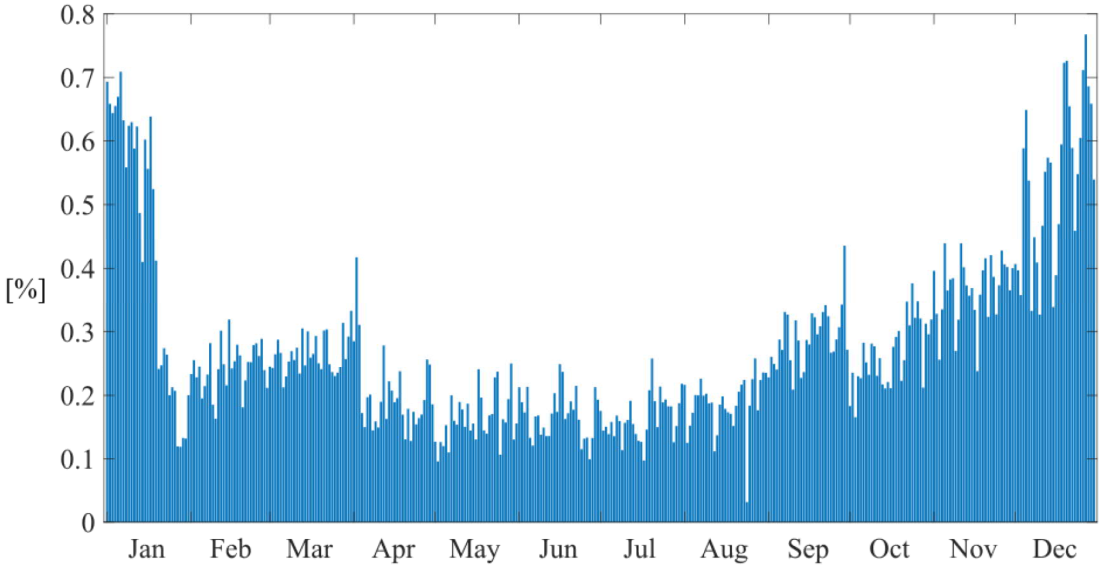


Figure 26: Distribution of the distance travelled by the identified recreational watercraft in East Asia in 2017.

Figure 27 shows how the activity of the identified recreational watercraft is distributed over the hours of the day and days of the week. Hourly distribution shows an increase in the activity during the day time, but the activity remains high also during the night. Also, the activity peak is wide and decreases slower than in other regions. There are no strong trends in the activity of different days of the week, but a small increase in the activity can be observed during Wednesday, Thursday and Friday.

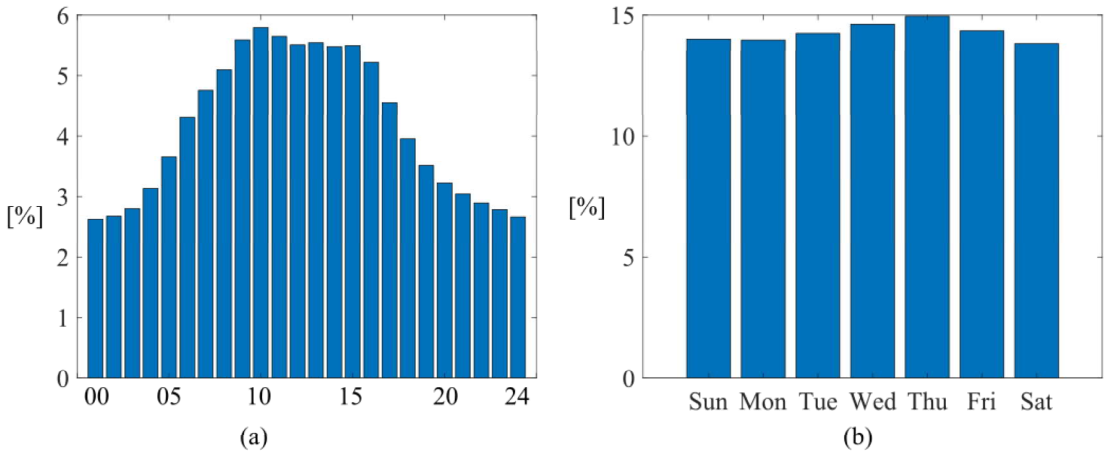


Figure 27: Hourly (a) and daily (b) distributions of the recreational watercraft activity in in East Asia.

5.5 Boating in Southeast Asia and Oceania

A total of 569 leisure marina locations have been reported in the OSM dataset in the Southeast Asia and Oceania. These locations are shown in the figure 28. Recreational boating marinas are concentrated especially around the archipelago of Southeast Asia and Maldives. In Australia, marinas are mostly located at the East coast where also the largest cities are.

Figure 28: Locations of recreational marinas according to the dataset by Open Street Map (OpenStreetMap contributors 2018).

A total of 1575 recreational watercraft were identified in the Southeast Asia and Oceania. Figure 29 shows the distribution of the identified recreational watercraft in the Southeast Asia and figure 30 in the surroundings of Australia. Hot spots of the activity are in the Gulf of Tonkin, the surroundings of Bangkok city in Thailand, the Singapore Strait and the surroundings of Manila city in Philippines. In Australia, the boating activity is concentrated at the east coast. Nearly all the regions show increase in the activity from September to February. However, in the Gulf of Tonkin the activity is at the highest in March to May.

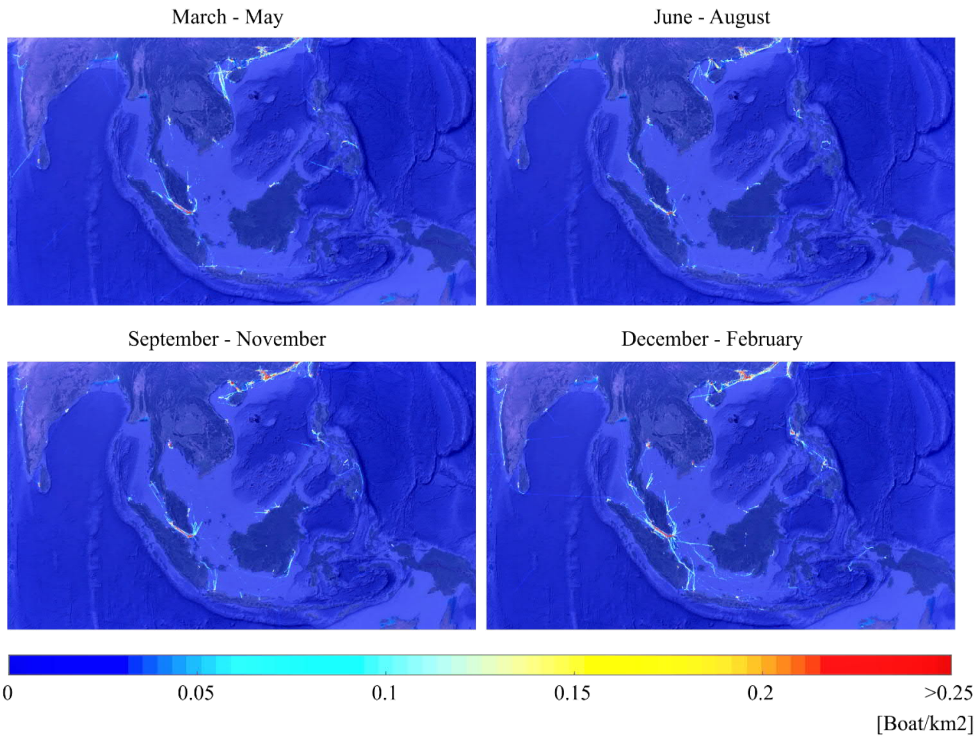


Figure 29: Number of identified recreational watercraft visits in Southeast Asia 2017.

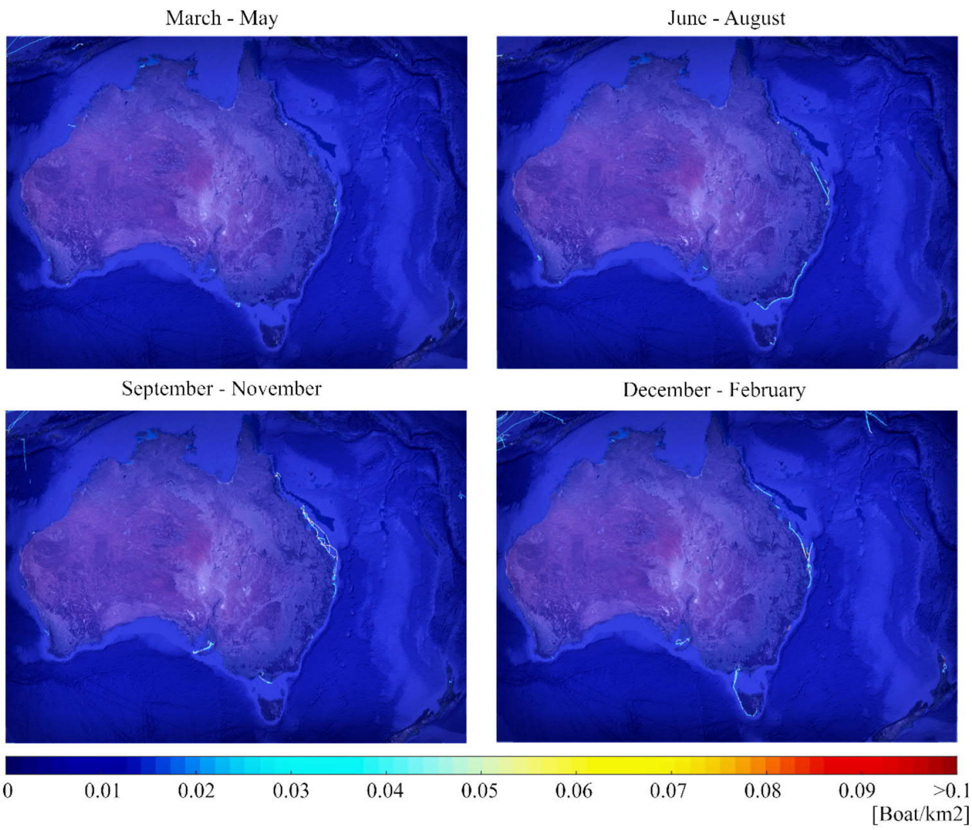


Figure 30: Number of identified recreational watercraft visits in Australia 2017.

Figure 31 shows distribution of the boating activity during the year 2017 in Southeast Asia and Australia. Boating activity level is at its lowest in June and July and increases from September to February. The most popular months for boating are November, December, January and February and the highest activity take place in the end of the December.

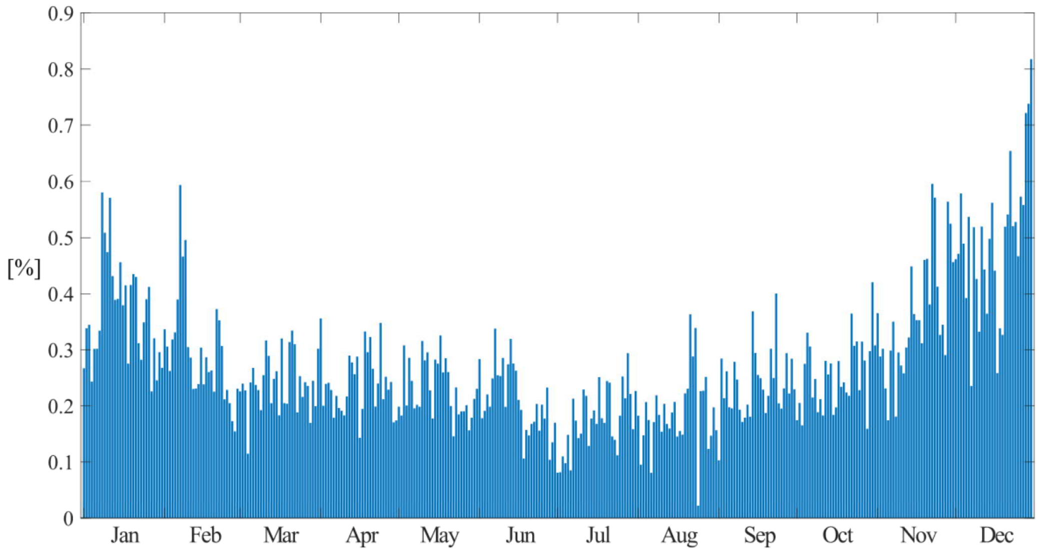


Figure 31: Distribution of distance travelled by the identified recreational watercraft in Southeast Asia and Oceania in 2017.

Daily and weekly activity trends of the recreational watercraft are shown in figure 32. The activity increases during the day time and the daily maximum occurs at 11 – 12 am. The activity remains at a relatively high level also during the night. The variation between the activity levels of different days of the week is larger than in other regions. Activity level is at the highest during Saturdays and at its lowest during Mondays.

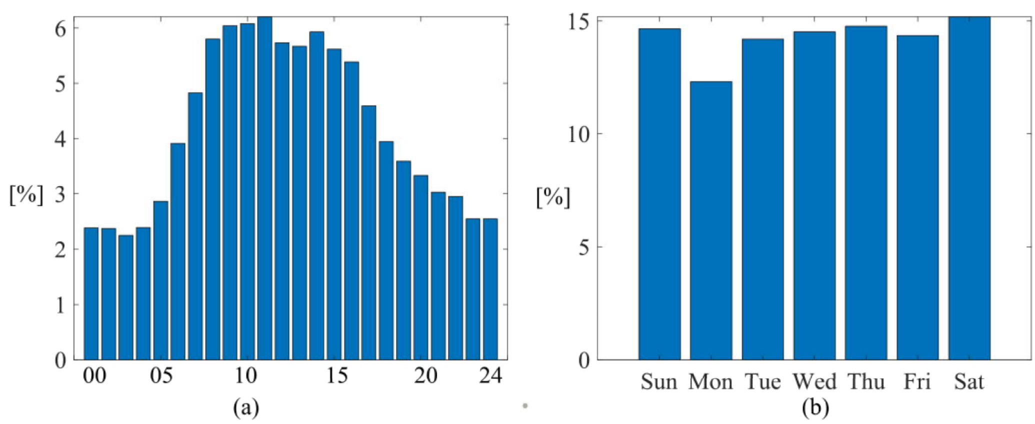


Figure 32: Hourly (a) and daily (b) distributions of the recreational watercraft activity in Southeast Asia and Oceania.

5.6 Boating in the Netherlands

The Netherlands is one of the most interesting areas for studying the boating activity due to the AIS subsidy campaign, which has led to a large number of recreational watercraft being fitted with an AIS. Therefore, a more detailed analysis was conducted for the water areas surrounding the Netherlands. A total of 3008 recreational watercraft were identified to travel in this area. Geographical distribution of the activity of the identified recreational watercraft in different seasons in the Netherlands is shown in figure 33. Activity rates are at their highest during the summer and at the lowest during the winter season. Strongest seasonal changes in the activity can be observed in the areas near the coastline, while some boaters who travel further to the sea seems to remain active around the year.

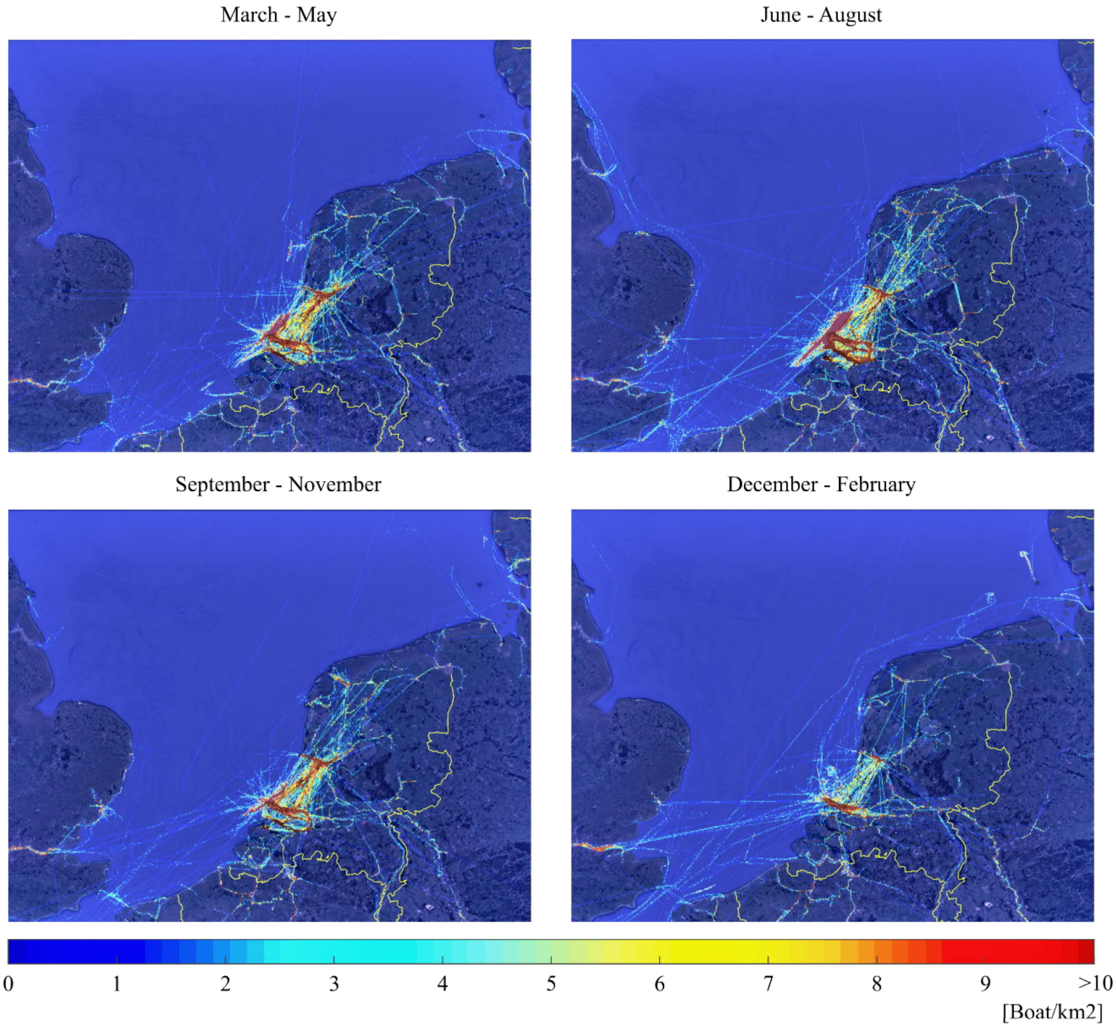


Figure 33: Recreational watercraft visits in the Netherlands in different seasons of 2017. Plotted on Google Earth.

Figure 34 shows the total number of visits of the identified recreational watercraft during 2017 and locations of recreational marinas in the area of the Netherlands according to satellite images of Google Earth. Boating activity takes place mainly at the sea areas within 20 − 30 km from the coastline and on inland waterways, but longer trips can also be observed. However, most of the boats travelling longer distances still travel along the coastline instead of going to the open sea. Near the English Channel, where the distance to the shore of the Great Britain is shorter, more boaters have crossed the Channel instead of remaining near the coastline of the Netherlands. A large number of leisure marinas is concentrated in the surroundings of Amsterdam and Rotterdam where also boating hot spots are located. However, there are areas with a high number of identified recreational watercraft, but no or only few leisure marinas. Marinas are mainly located along the inland waterways or in the gulfs and therefore, the boating activity at sea can be mainly observed at the mouths of rivers and gulfs. It seems that in inland waterways, the boating activity can remain high even at long distances from the nearest marina.

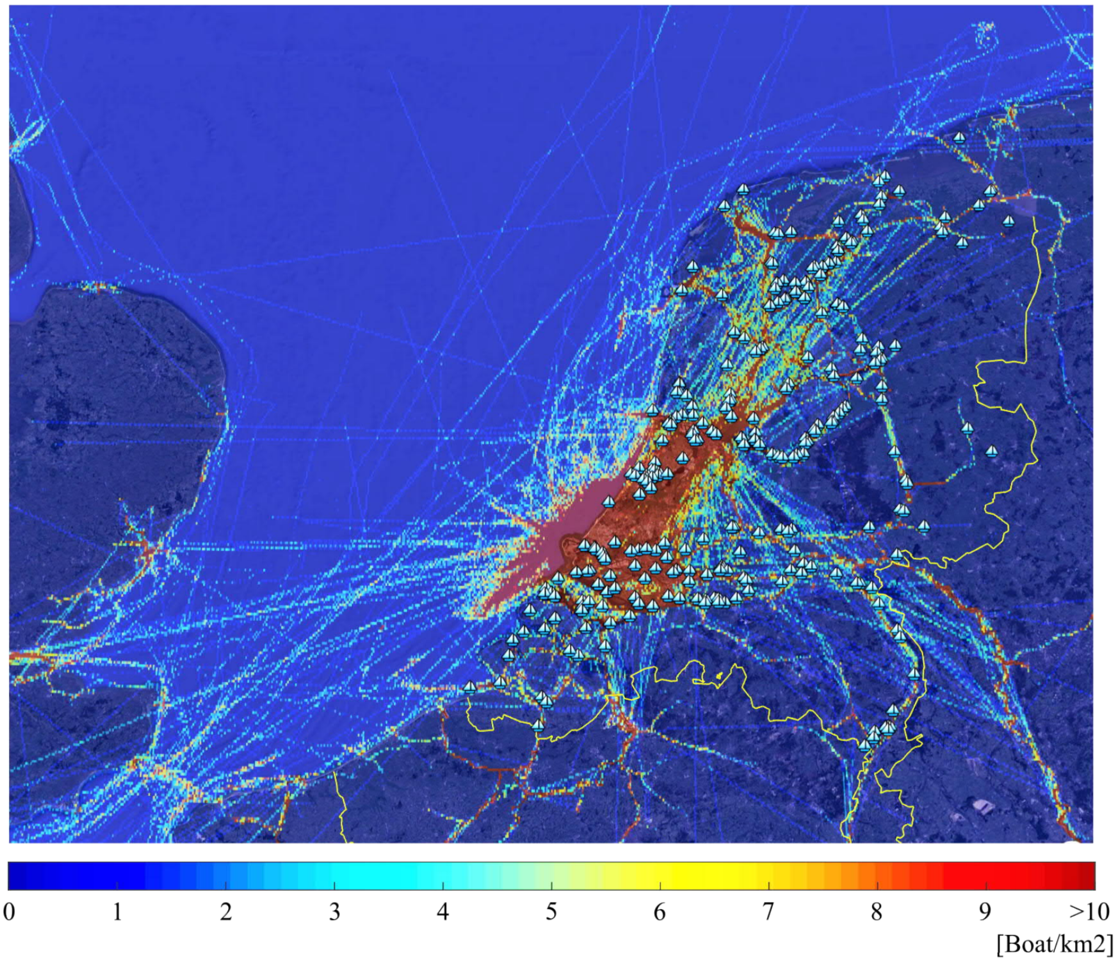


Figure 34: Total number of boat visits in 2017 and locations of recreational marinas (sailboat icons) in the area of the Netherlands. Plotted on Google Earth.

The yearly distribution of the boating activity in the Netherlands is shown in figure 35. The activity increases starting from the beginning of April and reaches the highest rate in the end of July. Boating activity remains at a high level in August, but decreases rapidly in the end of the month. Some days with a high boating activity level can be observed during the autumn season, but the activity remains low in comparison to the summer. The lowest boating activity take place during February and March. A large variation between the activity levels of different days can be observed.

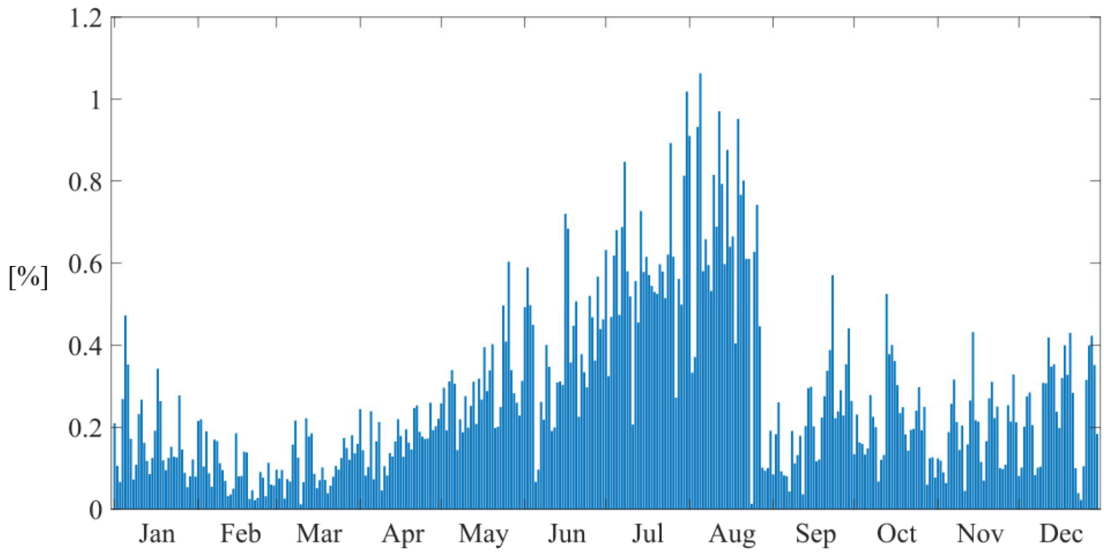


Figure 35: Distribution of the recreational watercraft activity in the Netherlands.

Figure 36 shows the level of activity during different hours of the day and days of the week. The activity increases during the day time and decreases to less than one tenth of the daily maximum level during the night. The highest activity level can be observed between 10 am and 11 am. The activity increases fast during the morning hours and decreases at slower rate during the afternoon. The variation between different days of the week is not large, but the activity is at a higher level during the weekend than during the week. Also, the activity is slightly increasing in the middle of the week and is at its lowest on Monday and Friday.

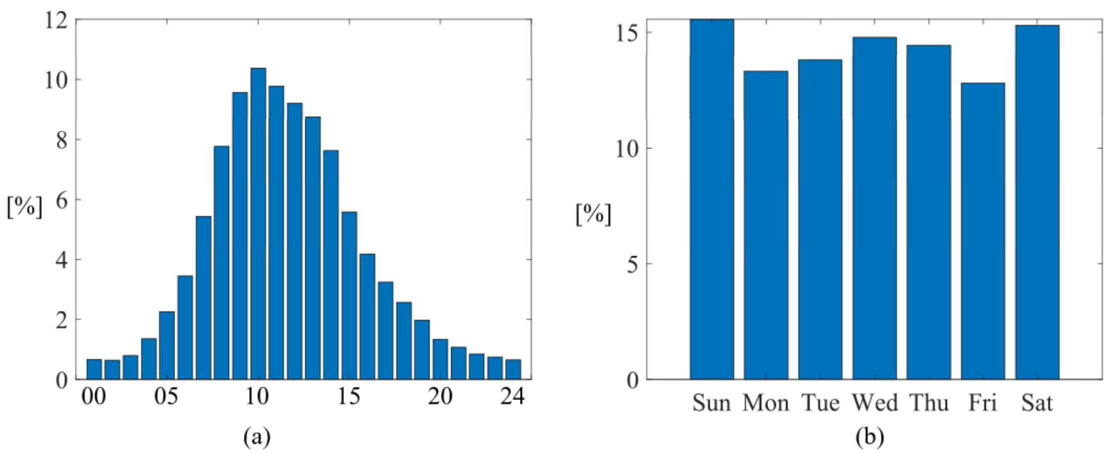


Figure 36: Hourly (a) and daily (b) distributions of the recreational watercraft activity in the Netherlands.

5.7 Environmental pressures

5.7.1 Atmospheric emissions

Air pollutant emission inventory guidebook by EEA (2016) provides instructions for building national atmospheric emission inventories. The guidebook lists emission factors that should be used to estimate emissions from different sources and it also includes emission factors for recreational watercraft. Emission factors are given for engines of different technology and age (table 3).

Table 3: Emission factors for recreational watercraft engines recommended by EEA (2016)

engine type	VOC [g/kWh]	NOx [g/kWh]	PM [g/kWh]
Gasoline, 2-stroke	31.51 - 254.69	2 - 3	10
Gasoline, 4-stroke	9 - 21.6	7 - 12	0.08
Diesel	1.58 - 2.17	8.6 - 18	1 - 1.4

In countries where recreational watercraft emissions are regulated, emission rates can be assumed to be below the set limit values. This assumption has been used for example in the emission inventory of Denmark by Winther and Nielsen (2006) to estimate emission factors of recreational watercraft. Emission limits for recreational marine diesel engines in USA, EU and China are given in table 5. Phase 1 emission limits in China will be used until january 2021 when stricter phase 2 emission limits will be applied. Limit values for emissions of recreational marine spark-ignition engines in USA and EU are shown in table 4. All of these regulations are only applied to new engines and therefore emissions from older watercraf engines can be assumed to be higher.

Table 4: Emission limits of hydrocasrbon and nitrogen oxides, and carbon monoxide [g/kWh] for recreational marine spark ignition (SI) engines in EU and USA.

P [kW]	CO (EU[1] and USA[2])	HC + NOx (EU[1])	HC + NOx (USA[2])
Sterndrive and inboard			
$P \leq 373$	75	5	5
$373 < P \leq 485$	350	16	16
$P > 485$	350	22	22
Outboard and PWC			
$P \leq 4.3$	500 - 5P	30	5.8
$P > 4.3$	300	$15.7 + \frac{50}{P^{0.9}}$	$2.1 + 0.09 * (151 + \frac{557}{P^{0.09}})$

(1) Council Directive 2013/53/EU
(2) EPA 40 CFR Part 1045

Table 5: Emission limits of hydrocarbons and nitrogen oxides [g/kWh] for recreational marine compression ignition (CI) engines in EU and USA, and the Phase I standard for domestic vessels in China.

SV [L/cylinder]	P [kW]	EU[1]	USA[2]	China[3]
Hydrocarbon and nitrogen oxide [g/kWh]				
SV < 0.9	P < 19	-	7.5	-
	$19 \leq$ P < 37	-	4.7	-
	$37 \leq$ P < 75	4.7	4.7	7.5
	$75 \leq$ P < 3700	5.8	5.8	7.5
$0.9 \leq$ SV < 1.2	P < 3700	5.8	5.8	7.2
$1.2 \leq$ SV < 2.5		5.8	5.8	7.2
$2.5 \leq$ SV < 3.5		5.8	5.8	7.2
$3.5 \leq$ SV < 5.0		5.8	5.8	7.2
$5.0 \leq$ SV < 7.0		5.8	5.8	7.8
Particulate matter [kWh]				
	$19 \leq$ P < 37	-	0.3	-
	$37 \leq$ P < 75	0.3	0.3	0.4
	$75 \leq$ P < 3700	0.15	0.15	0.4
$0.9 \leq$ SV < 1.2	P < 3700	0.14	0.14	0.3
$1.2 \leq$ SV < 2.5		0.12	0.12	0.2
$2.5 \leq$ SV < 3.5		0.12	0.12	0.2
$3.5 \leq$ SV < 5.0		0.11	0.11	0.2
$5.0 \leq$ SV < 7.0		0.11	0.11	0.27

(1) Council Directive 2013/53/EU
(2) EPA 40 CFR Part 1042
(3) ICCT 2017

EPA (2002) estimated baseline emission rates for recreational marine diesel engines by measuring emissions from 25 different engines. For a new engine, at the time, baseline emissions were estimated to be 0.295 g/kWh of HC, 8.94 g/kWh of NO_x, 1.27 g/kWh of CO and 0.219 g/kWh of PM. The average emission rates of different substances measured in the study are shown in figure 37.

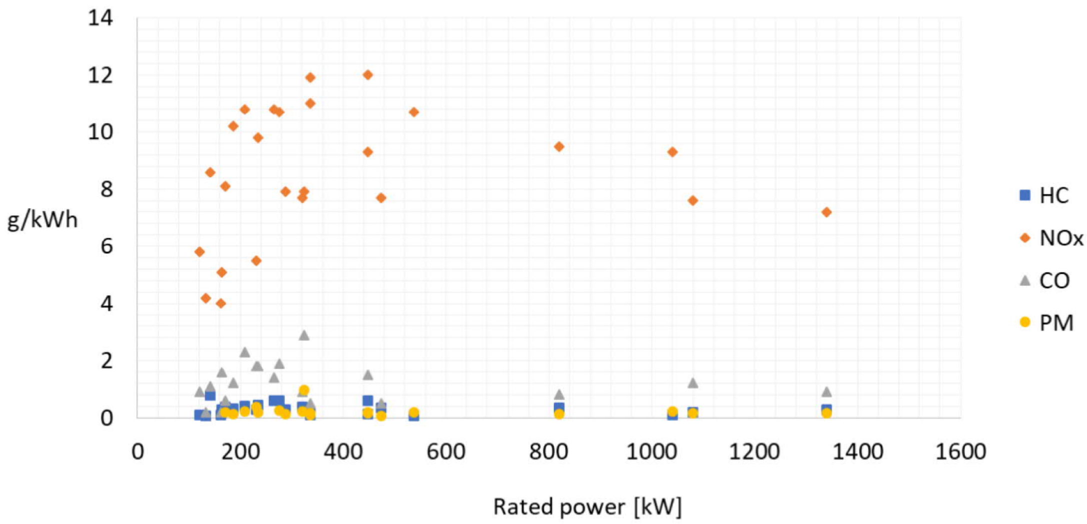


Figure 37: Measured emission rates of hydrocarbons (HC), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM) from recreational marine diesel engine (EPA 2002).

Gabele and Pyle (2000) and Jüttner et al. (1995) measured emissions generated by recreational gasoline engines. Figure 38 shows some results of these studies. Jüttner et al. (1995) also measured particulate matter emissions and reported average emission rates of 0.16 g/kWh for a two-stroke engine and 0.0007 g/kWh for a four-stroke engine.

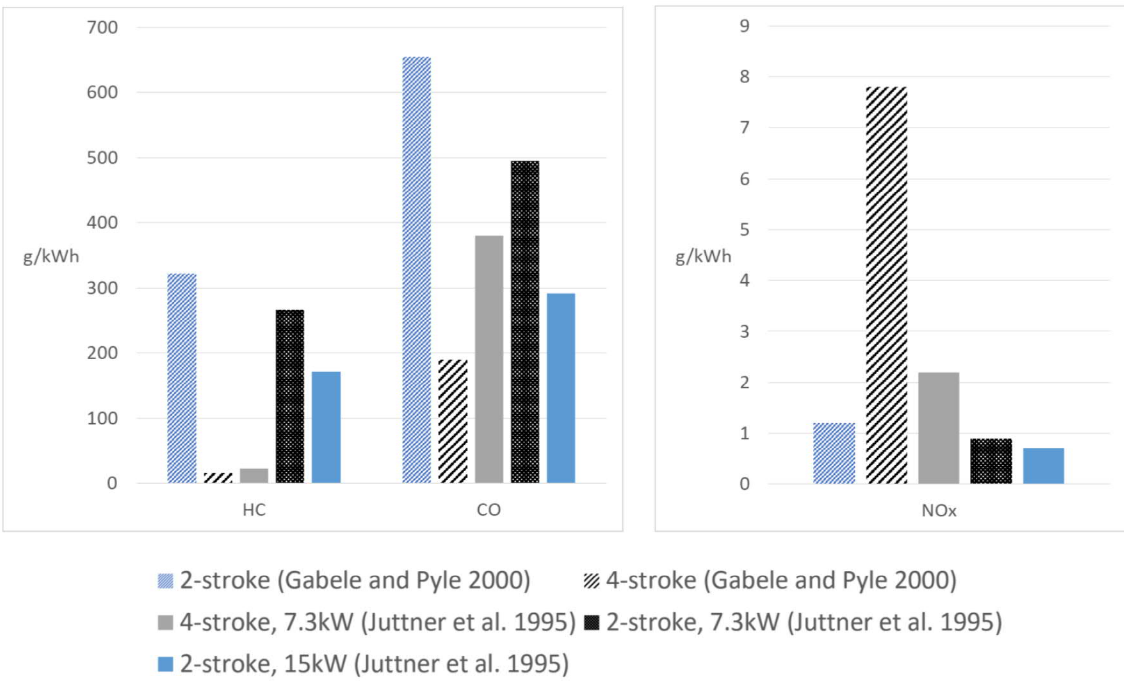


Figure 38: Measured emission rates of a recreational marine gasoline engine (Gabele and Pyle 2000; Jüttner et al. 1995).

Measurements of CO_2 emissions from recreational watercraft are scarce and therefore, emission factors are difficult to obtain. CO_2 emissions can be estimated based on the brake-specific fuel consumption (BSFC) of the watercraft, which is the fuel consumption rate divided by the produced power. For example, EPA (2004) uses the following equation for calculating CO_2 emissions from recreational watercraft:

$$f_{CO_2} = (f_{BSFS} - f_{HC}) * w_C * \frac{m_{CO_2}}{m_C}, \tag{8}$$

where $f_{CO_2} = CO_2$ emissions [g/kWh]
f_{BSFS} = brake-specific fuel consumption [g/kWh]
f_{HC} = Hydrocarbon emissions [g/kWh]
w_C = carbon mass fraction of the fuel [-]
m_{CO_2} = molar mass of CO_2 [g/mol]
m_C = molar mass of carbon [g/mol].

5.7.2 Emissions to water

According to a survey by Trafi (2017), antifouling paints are not widely used as only 10 % of participants reported to have their boats treated with antifouling paint. Paints were mostly used on seagoing vessels. The largest volume of antifouling paint per boat, an average of 1.4 litres annually, was consumed by sailboats of which 46 % had been treated with antifouling paint. In comparison, the volume of antifouling paint consumed per small outboard motorboat was only 0.03 litres during the year. The survey also indicated that surprisingly large number of waterjets used antifouling painting, which does not correspond to the general belief that the maintenance of PWC does not require antifouling painting. A similar survey conducted in Sweden by Lagerqvist et al. (2016) showed that approximately 16 % of boaters prevented biofouling by using bottom paint. The survey also supported the other survey results of antifouling paints being mainly used on seagoing boats and less on boats operating in inland waters. Ytreberg et al. (2010) conducted laboratory experiments to study leaching rates of Copper and Zinc in different eroding antifouling paints. The release rates of paints allowed in leisure boats varied between 0-1.1 μg/cm^{2}d for copper and 0-8.2 μg/cm^{2}d for zinc in natural sea water. Also Schiff et al. (2003) measured release rates of an antifouling paint on recreational watercraft. Average leaching rate of dissolved copper varied between 0.24 and 4.32 μg/cm^{2}d depending on coating. Hull cleaning increased the leaching rate even up to 17.45 μg/cm^{2}d if a best management practise was not used.

A survey conducted in Finland by Trafi (2017) showed that there is a correlation between boat size and installation of on-board toilet facilities. Motorboats with an outboard engine of the power of 20 hp or less generally had no toilet facilities, and only 5 % of larger outboard motorboats had some type of on-board toilet installation. However, 64 % of inboard motorboats, and 78 % of sailboats had an on-board toilet. The most common type of on-board toilet is a pump-out toilet with a septic tank while the second most common type is a chemical toilet with a removable tank. There were also some boats with a septic tank intended to be emptied directly into the water. Additionally, some responses indicated that even in boats without installed toilet facilities, some type of a tank is used for storing wastewater. Similar results were shown in a survey from Sweden by Lagerqvist et al. (2016). Majority of boaters (approximately 90 %) did not have a permanent toilet on their boat. The most common toilet type was a tank with a pump-out discharge outlet and the second most common was a holding tank, which is emptied directly into the sea.

Gabele and Pyle (2000) measured hydrocarbon emissions into water phase during the opeartion of two gasoline engines. Average emission rates of different compounds are shown in figure 39. Emissions of MTBE from a two-stroke engine are significantly higher than other measured emissions with an average of 6.91 g/kWh while release rates of other compounds remain below 1 g/kWh. The study also reveals that emission rates depend on the travel speed, but the optimal speed in terms of achieving lower emissions depends on the type of the engine.

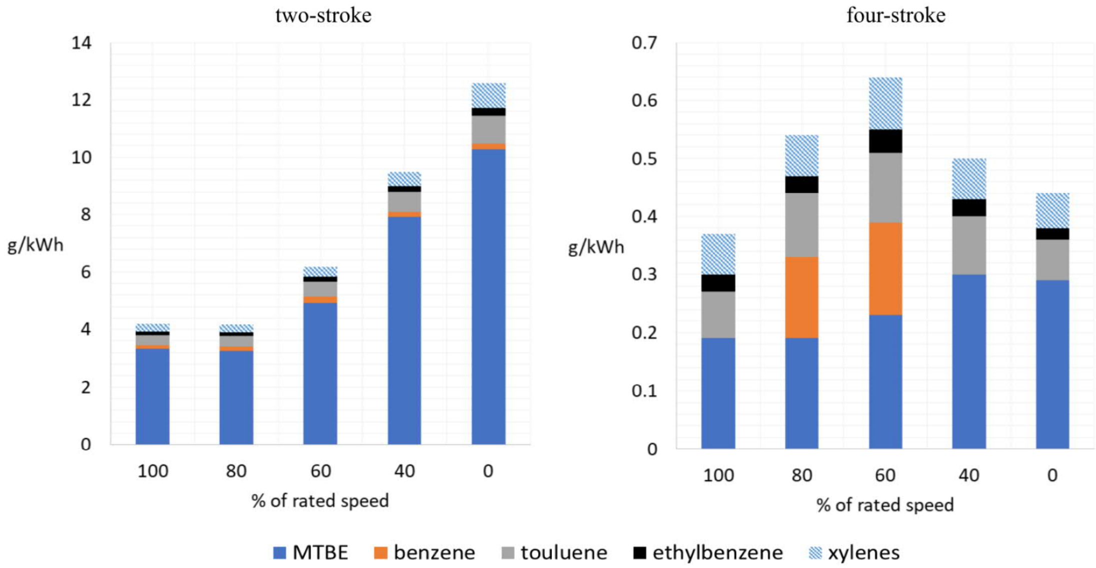


Figure 39: Hydrocarbon emission rates of two gasoline engines into water (Gabele and Pyle 2000).

6 Discussion

6.1 Activity profiles

The generated activity profiles around the world show that the boating activity is concentrated in inland waters and in the sea areas within 20 – 30 km from the coastline. Archipelago, or other land areas near the coast, may increase the range of the boating activity at the sea. It can be assumed that generally boaters want to remain close to the land for safety purposes. It might be important to be able to return to the shore quickly in case of an accident or a technical failure, but also the sailing conditions on the open sea are often more challenging than in the archipelago and near the coast. These results are in line with the available results from surveys which suggest that majority of the boaters stay within 40 km from the shore. There is evidence that some boaters travel longer distances at the open sea, but these boats were most likely filtered out from the analysis due to the activity limitations used.

Temporal activity profiles show that the seasonality of the boating activity varies. In northern areas, the climate strongly affects the boating conditions and therefore, a clear seasonal variation can be observed. In the regions near the equator, such a clear trend cannot be expected. In Europe, there is a trend of the activity increasing from early spring to July and August and then decreasing during autumn. In the Netherlands, this profile is even sharper and the boating activity is mainly concentrated on July and August. These results are in line with the results from the boating surveys, as majority of boaters had reported to be active mainly during the summer season. In North America, a slight increase in the boating activity can be seen during the summer season, but the highest activity rates are observed during the winter. Seasonal variations in the spatial activity profile of the North America show that in the north region, the boating activity is at its highest level during the summer season. High activity levels during the winter are therefore due to the boating activity in the south of the USA. One explanation for the popularity of the winter season for boating in the south part of USA can be the Atlantic hurricane season, which takes place from June to November (Virmani and Weisberg 2006).

In the Southeast Asia and Oceania, the most active boating season extends from September to February. This is in line with the results from the boating survey conducted in Australia. Additionally, the monsoon season and the highest frequency of typhoons in the Southeast Asia takes place from June to November, which might explain low boating activity during these months (Imamura and To 1997). The algorithm identified relatively high number of recreational watercraft in the area of East Asia. Results are surprising as the boating activity seems to be concentrated in the coastline of China, where the estimated size of recreational watercraft fleet is still small in comparison to Europe and North America. Moreover, the level of boating activity increases during the winter season also in the northern regions, where the average temperatures are below zero degrees during the winter. One explanation could be that small fishing vessels are falsely identified as recreational watercraft.

The high activity level during the winter is in line with the summer fishing ban of Yellow Sea, East China Sea, Bohai Sea and South China Sea, which normally takes place from June to September or August (Goldstein 2013). Another reason could be the monsoon season, which also affects East Asia during the summer and autumn.

All regions observed in this study show similar daily activity distributions; the activity increases rapidly in the morning, is at the highest just before the noon and decreases slowly towards the evening. This is in line with boating survey results showing that the most popular time for boating is from 6 am to 2 pm. Majority of the regions showed a low level of activity between 22 pm and 5 am, which supports the current knowledge as only few boaters have reported to be active during the night. Night-time activity should be most likely considered to be an evidence of false detections, instead of a proof of boat activity. In the Netherlands, where the number of AIS fitted on recreational boat is high, the level of boating activity during the night is lower than in other areas. This supports the assumption of the night-time activity being an indicator of errors in the activity profiles. It is also possible that in some regions, non-commercial fishing is increasing the activity during night.

Most of the regions show surprisingly weak differences between weekends and weekdays. According to the boating surveys, the boating activity should be higher during the weekends in comparison to weekdays. Also, a study by Henry (2013) revealed large differences in concentrations of gasoline related hydrocarbons at coastal site between weekdays and weekends, which is most likely due to the effect of changes in the level of recreational boating activity. From all studied regions, only the Netherlands area showed a trend of higher activity during Saturdays and Sundays. Minor weekend – weekday differences could be caused by false detections or by high activity rates during holidays that take place during the weekdays. Also, it is possible that the number of recreational watercraft represented in the AIS data are more active during the whole week than boats without AIS transmitters. The smallest recreational watercraft can be assumed not to be well represented by AIS data and these boats might be mainly used during the weekends whereas larger watercraft might be used for longer trips of several days. Although the total travelled distances during different weekdays do not generally show large variation, distribution of the activity over the year shows that there is a large variation in the activity level between individual days. This might be an evidence of the boating activity rate changing rapidly for example, due to changes in the weather.

The accuracy of the results was evaluated by comparing them with results of the boating surveys and locations of leisure marinas according to the OSM dataset. There are spatial differences in how well the algorithm seems to perform, which is not surprising due to possible variation in the representativeness of the identification criteria and differences in the coverage of the AIS network. In northern Europe, spatial distribution is in line with the distribution of leisure marinas. The Netherlands is overly represented most likely due to higher number of AIS in small boats compared to other regions. However, in the southern region of Europe, the coastline of North

Atlantic Ocean shows boating activity significantly higher than the Mediterranean Sea, which does not correspond to the distribution of leisure marinas. Also, the large number of recreational marinas in the Netherlands makes it difficult to estimate the correlation between locations of marinas and the boating activity. However, the largest boating hot spots and the highest leisure marina densities seem to be located in the same areas. High boating activity levels during the cold season and during the night in the area of East Asia give a reason to suspect the accuracy of the results. High activity levels during the night can also be observed in Southeast Asia. Criteria for the identification of recreational boats are based on boating surveys from a limited number of countries and therefore, it is possible that the algorithm is not able to efficiently detect recreational watercraft in other regions. It is also possible that a low number of recreational watercraft in the area will lead to relatively large effect of falsely identified watercraft on the activity profiles.

6.2 Environmental pressures

Currently, it is not possible to quantify the emissions generated by recreational watercraft as the number of different boat types is not known in most countries. Existing regulations and emission factors can be used to obtain information of the level of these emissions. One major challenge to estimate the emissions is the variation of emission rates between different boat types and engine types. For an average petrol engine, the most significant exhaust emissions are hydrocarbons and carbon monoxide, but for a diesel engine, oxides of nitrogen are more important. Moreover, emission rates depend on the level of the technology, the power and the age of the engine, and also, on the operating behaviour and the level of maintenance. According to the available emission factors, older low power petrol engines have the highest level of exhaust emissions per produced power. Emission limits only consider new engines and therefore, even after stringent emission limits are introduced, the variation of exhaust emissions rates will remain large for several decades.

For other emissions than the engine exhaust, estimating the emissions rates is even more challenging. Exhaust emissions can be estimated as long as there is enough data about the recreational marine engines, but for other emissions, understanding the behaviour of the boater might be more important than the technical characteristics of the boat. According to the boating surveys, majority of boaters do not use antifouling paints and for those who choose to use these paints, several different options of paint products are available. Moreover, the maintenance work of the boat can release contaminants into the environment if necessary measures, such as collecting the wastewater and particles from the hull cleaning, are not performed. Also, the significance of other emission sources, such as wastewater and solid waste, depend on the behaviour of the boater. Level of noise emissions depends on the engine and the structure of the watercraft, but again, the behaviour of the boater might play even more important role.

Activity profiles show that the boating is concentrated on the warmest season of the year. This implicates that in regions of colder climate, the boating season is shorter and therefore the period of emissions being generated is also shorter. However, it also means that emission peaks might be higher during the suitable time for boating than in areas where the boating period is longer. Spatial distribution supports the assumption of boating activity being most intensive near highly populated areas. Especially inhabitants and the environment in the surroundings of leisure marinas can be assumed to be affected by the emissions of recreational watercraft. Antifouling paints will continue leaching to the water also when the boat is berthed and maintenance work, which is often done at the marina, increases the release rates of the paint. Moreover, during travelling emission rates depend on the speed of the boat and for example hydrocarbon emissions from two-stroke engine are at the highest when the boat is idling or moving at low speed. In a marina, the boat can be assumed to move at lower speed than at the sea, which might increase the emission rates.

As the boating emissions are strongly dependent on the decisions of the user, national boating surveys might be a necessary tool for estimating the level of these emissions. There has been some development in the emission standards of recreational watercraft, but the limit values are still lacking behind the limitations of other transportation modes. For example, maximum allowed CO emissions from heavy-duty vehicle engines is 4.0 g/kWh, which is significantly lower than the 75 – 350 g/kWh allowed for a recreational marine engine. Similarly, the emission standard for the heavy-duty vehicle engines are 0.16 g/kWh for HC and 0.46 g/kWh for NOx, when the allowed HC+NOx emissions from recreational watercraft is 4.7 – 30 g/kWh in total. (ICCT 2016) The light regulation of recreational boating can at least partly explain the high impact of a boater's choices on the level of environmental pressures caused the activity. Differences in the boating activity results might implicate that the boating culture is very different in different parts of the world. In some areas, non-commercial boating might be vital for people in terms of fishing for own consumption or transportation. In these areas, restricting boat emissions might have more negative impacts on the society than in areas, where boats are mainly used for leisure purposes.

6.3 Suitability of AIS for tracking recreational watercraft

Activity profiles generated with an AIS dataset can be assumed to be non-representative of the total recreational watercraft fleet. On-board AIS transmitters are generally not required on recreational watercraft and therefore, boaters using this equipment are most likely using the boat more frequently and for traveling longer distances than an average boater. The smallest of recreational watercraft are most likely not represented in AIS and therefore, other methods should be used to verify their activity. In some areas, such as the Netherlands, where the usage rate of AIS is high, this issue can be assumed to be less significant. Also, as the intensity of the activity is used as a criterion for the identification of recreational watercraft, boats used at the highest intensity will most likely not be represented in the results. However, restricting the criterion for the total distance travelled and the number of days the boat is used might increase the number of false detections.

When analysing the spatial distribution of the boating activity, comparison between different regions should be avoided as the coverage of AIS network and the usage rate of AIS among boaters is not constant. Spatial distribution of recreational boating activity based on AIS data will be biased showing relatively high activity rates for areas with a good AIS coverage and legislation or subsidies that support the usage of AIS on boats. However, on local level, where the legislation or AIS network coverage is not varying significantly, the comparison of the intensity of the activity is possible. A low AIS coverage might also falsely increase the number identified recreational watercraft as only a fraction of AIS messages are received and thus the activity of the vessel might be underestimated. This can be assumed to be the reason for unrealistically high proportions of vessels identified as recreational in some regions.

To further evaluate the performance of the proposed method, a comparison with results from other tracking method, such as radar or satellite images, should be conducted. Comparison between known locations of recreational marinas and geographical distribution of identified recreational watercraft can provide some information about the accuracy of the identification of recreational watercraf. Also, results of available boating surveys can be compared with the activity profiles. However, results from surveys and locations of leisure marinas reported by volunteers may both contain errors. In northern Europe, where the boat density is high and AIS coverage good, the activity profiles seem to be well in line with the known locations of leisure marinas and the boating survey data. Furthermore, in southern Europe, North America, Southeast Asia and Oceania, results are largely corresponding to the existing knowledge, but a low number of identified recreational watercraft in many regions make results less reliable. A large number of watercraft were identified as recreational in East Asia, but the generated activity profiles give reason for suspecting a low performance of the algorithm in this area.

6.4 Uncertainties

Criteria for frequency of boating and distance travelled are strict enough to filter some of the largest recreational vessels out of the data. However, possibility for other vessel types to be identified as recreational craft need to be considered. The effect of false detections on activity profiles is most likely the highest in areas where the total vessel activity is high, but the number of recreational watercraft with AIS is low. Also, as the criteria given for behaviour of recreational watercraft are based on a limited number of boating surveys, it can be assumed that the performance of the algorithm is better in areas represented by these surveys. Boating surveys used for the study have been conducted in Northern Europe, North America and Australia and it can be assumed that the boating culture for example in Asia differs from these countries. Moreover, regions covered by the available boating surveys are mainly located in a climate with seasonal variation when in regions closer to the equator, the length of the boating season is most likely longer.

In this study, the boating activity was studied based on a period of one year assuming that it represents the general situation. Recreational boating, as an outboard sport, is strongly dependent on the weather conditions and therefore, activity profiles generated without weather dependency might not be representative of other years. Also other factors than the weather, such as the economic situation and fuel prices, can affect the popularity of boating, but are not taken into account in the proposed method. To include these factors in the activity profiles, a dataset with sufficient AIS coverage of recreational watercraft would be needed for a longer time period than the one year used in this study.

The boating activity rates are based on the total distance travelled by recreational watercraft. The estimation of the travel path and distance require simplifications, which might affect the results. Boats are travelling near the coastline, in archipelago and in inland waters where different obstacles and land areas might affect possible routes. However, they are assumed to travel the shortest possible path and this might lead to underestimation of the travelled distance and errors in the spatial distribution. Also, the radius of the earth was assumed to be constant, which will cause some level of error in the calculated distances. However, errors caused by these simplifications will most likely not lead to significant level of errors in the activity profiles, because the travel distance was used to estimate the variation in the intensity of the activity and not to estimate the actual total distance travelled by recreational watercraft.

6.5 Future prospects and recommendations

As the number of boats fitted with AIS seems to be increasing, the proposed method would be more widely suitable in the future. Also, recreational watercraft tend to use class-B AIS transceivers, which have lower reach than most powerful transceivers, and thus development in the receiver technology and coverage would increase the number of weaker AIS signals received. To obtain a better understanding about the performance of the method, a comparison with other tracking methods should be conducted. If the number of recreational watercraft fitted with AIS continue to increase in the future, finding correlation between different weather conditions and the boating activity could enable more sophisticated modelling of the boating activity. This would however require a dataset representing a longer time period, with a sufficient number of recreational watercraft, but could bring more accuracy to estimating environmental pressures caused by boats, especially in areas of strong seasonal variation.

The information about recreational watercraft activity obtained from the AIS dataset could be combined with other available information, such as locations of leisure marinas. Regions with sufficient AIS coverage can be used to estimate the average distribution of the activity in the surroundings of a leisure marina. This distribution could be applied in the regions where the AIS coverage of recreational watercraft is not high enough, but locations for leisure marinas are known. Results from this study show that the majority of boaters stay within 30 km distance from the coastline and this range could be used in the surroundings of a coastal marina to describe the boating activity. Recreational watercraft not represented by the AIS dataset are most likely active in a smaller range from the marina than the proposed 30 km. For inland waters, this range is most likely larger and further studies are required to estimate how far boaters travel for example from a marina located in a river.

Exhaust emission can be controlled, but not totally avoided as long as the internal combustion engines are the main engine type in the market. However, most of the emissions to the water phase could be avoided or at least significantly decreased. As recreational watercraft are used for leisure purposes, avoiding unnecessary emissions would not result in as significant economic impact as controlling the commercial marine sector. Ensuring the availability of solid waste and wastewater collection services, as well as toilet facilities, at the largest recreational marinas could already decrease the amount of waste discharged to the marine environment. Banning the use of antifouling paints in the smallest boats, which are most likely operating inside a limited area, would not increase a risk of invasive species spreading to the new areas by being attached to the hull of a boat. There are several mechanical methods available for preventing and decreasing the biofouling on the boat hull that do not require the use of toxic substances. Also, availability of proper equipment for the maintenance work of the boat and for the refilling would decrease the amount of hydrocarbons and paint particles in the environment.

One of the biggest challenges for conducting this study was the lack of existing information about recreational boating. National boat registries or boating surveys are necessary for more precise understanding of the extent of environmental impacts of boating activity. This would require actions on local level as behaviour of boaters most likely vary by the location. With more detailed information about boating cultures, criteria for the identification of recreational watercraft could be given separately for different regions. Moreover, more detailed information about the number of recreational watercraft and boat types are necessary for constructing more advanced emission models. This information could also be gained by boating surveys and registries. Additionally, a study more focused on certain areas with high AIS coverage of recreational watercraft could provide results with higher accuracy as more specific identification criteria could be used.

The results of this study support the previous knowledge about boating being highly seasonal activity and concentrated on near coastline and inland waters. This means that even if emissions caused by recreational watercraft could be neglected in global emission inventories, on local level they should be considered. Areas with high intensity boating should aim to evaluate environmental pressures caused by the activity and update corresponding legislation so that boating would not cause excessive stress on the surrounding environment. As the boater can affect the level of environmental pressure caused by the boating activity, education of boaters about environmental impacts of boating is recommended. However, more stringent legislation on the engine emissions and on the chemicals in antifouling paints, and better services at recreational marinas, would reduce the responsibility of the boater.

7 Conclusions

The main airborne emissions from recreational watercraft include volatile hydrocarbons, carbon monoxide, oxides of nitrogen, particulate matter and carbon dioxide. As the contribution of recreational watercraft to the climate change is small in comparison to the commercial fleet, emissions affecting the ambient air quality can be considered to be more significant than greenhouse gas emissions. Hydrocarbons, biocides of antifouling paints and wastewater are the most significant emissions to the water. Rates of these emissions vary widely depending on the boat type and operation. The legislation controlling these emissions is clearly lacking behind in comparison to other transportation sectors. Especially the emission limits of carbon monoxide and hydrocarbons are significantly higher for recreational marine engines than other engine types. The level of environmental pressure caused by boating depends largely on the behaviour of the boater, which can be explained by the lacking regulation of boating emissions.

There are several methods for tracking boating activity. Boating surveys are the most widely used and maybe the simplest approach to study boaters' behaviour. Satellite and radar images have been used to detect boats and they have a large potential, but the noise in images and low spatial or temporal resolution makes detection of the smallest boats challenging. Safety and rescue statistics could also be used to estimate boating activity. The use of AIS data to generate boating activity profiles would be efficient as extending the method to new areas or new time series would not require a big effort. However, the share of the recreational watercraft fleet that is visible in the AIS is most likely not representative of all the watercraft. Installing an AIS is not compulsory for recreational watercraft and therefore, the smallest and the least used boats are most probably not fitted with such equipment.

Activity profiles seem to be accurate in areas of high boating activity and high AIS coverage of recreational watercraft. In other areas, the activity profiles might be unreliable due to the possible effect of false detections. Results support the previous knowledge about boating being a strongly seasonal activity and concentrated on limited area. Most of the boaters are active during the warmest season of the year and at the day time. In areas of monsoon or storm seasons, the boating activity is most likely less frequent during these seasons. Majority of the environmental pressure caused by boating will focus on the sea areas within 20 – 30 kilometres from the coastline, and inland waters. Archipelago or other land areas near the coastline may increase the spatial range of the boating activity. The variation in the boating activity between different days seem to be large and it can be assumed that the weather and possible holidays will affect the level of activity.

The AIS coverage of recreational watercraft has been estimated to increase and therefore, the use of AIS to track the boating activity might have more potential in the future. However, the smallest boats will most likely remain outside of the reach of the system and therefore other methods might be needed to cover activity of all recreational watercraft. In areas of high boating activity levels, more attention should be paid to environmental impacts of boats. More stringent legislation would decrease the boaters' responsibility in ensuring the sustainability of their boating. Majority of environmental issues related to boating are effective on local level and therefore, local authorities should be involved in developing a more sustainable boating culture. In coastal areas, the range of 30 km from the coastline could be used to generate distribution of the boating activity according to the locations of leisure marinas. For inland waters, further studies are needed to estimate the range of boating activity.

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